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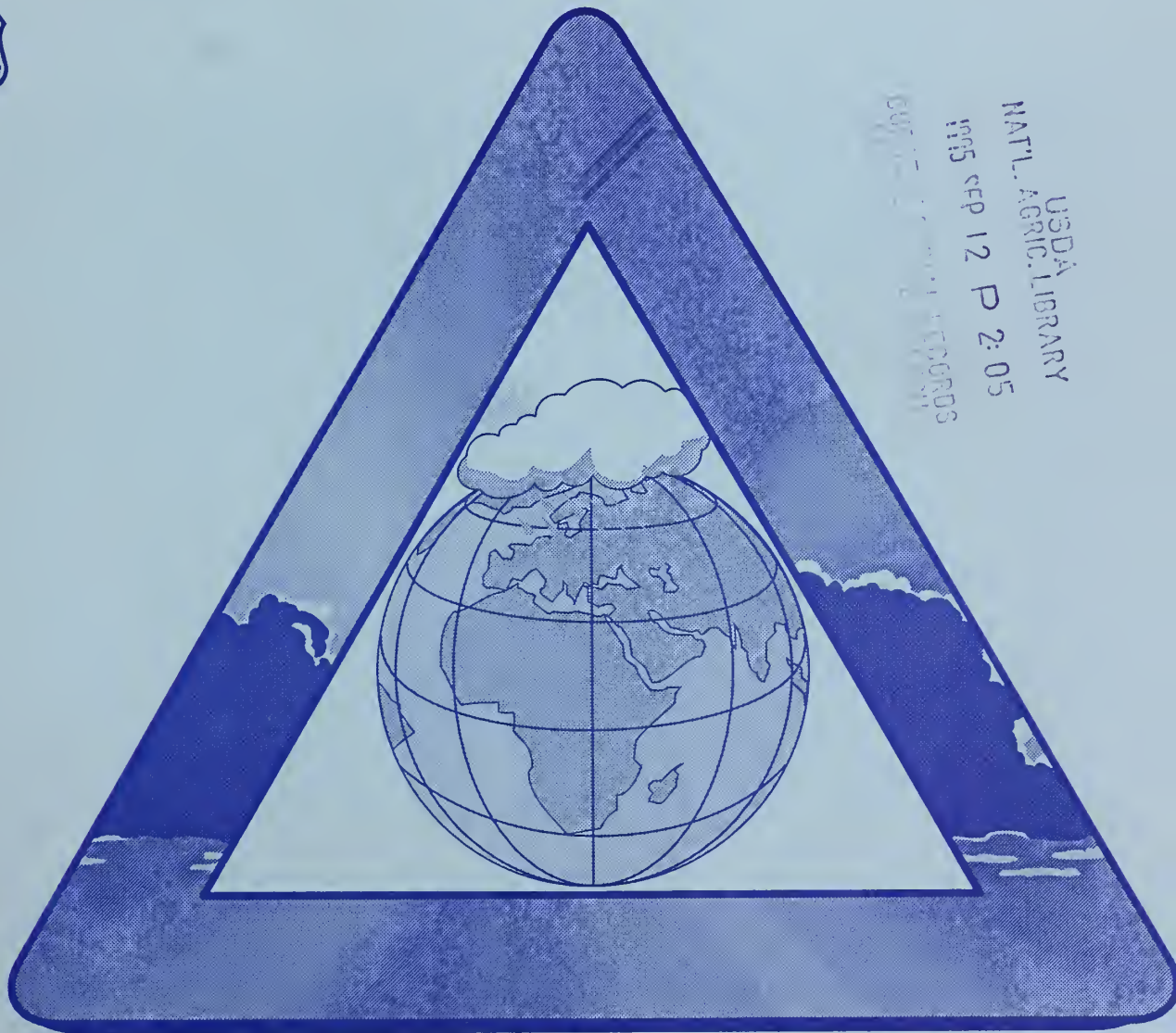
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# Interior West Global Change Workshop

April 25-27, 1995, Fort Collins, Colorado



## **Abstract**

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Research accomplishments of the Interior West Global Change Program are outlined herein, and workshop participants discussed management implications of the results. Action to be taken now includes establishing monitoring systems to detect changes and guide management, and to maintain resilient ecosystems capable of responding successfully to change in any direction.

**Keywords:** global change, climate change, ecosystem management, monitoring.

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## Interior West Global Change Workshop

April 25-27, 1995, Fort Collins, Colorado

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## Foreword

The Interior West Global Change workshop was held April 25-27, 1995, in Fort Collins, Colorado. Its purpose was to chronicle the research achievements of the Global Change Program over the past 5 years, outline the implications of these research results for natural resource management, and lay out what further research is needed. Twenty one scientists from three experiment stations, two universities, and the Washington Office participated. This Report begins with our conclusions about what these results mean to natural resource

managers and is followed by the individual research papers and summaries.

Opinions expressed in these papers are those of the authors and do not necessarily represent the positions of the USDA Forest Service or Department of Agriculture.

We thank the authors for their participation and for promptly submitting their papers in both paper and electronic form, which has made it possible to publish this Report so quickly. For that reason, the papers did not receive normal editorial review.



# Research Accomplishments of the Interior West Global Change Program: Management Implications

Richard W. Tinus<sup>1</sup>

There are several management implications of global change research. Some are broad and cannot be site-specific, but indicate things to watch for. Others point to management actions that can be taken now. This section is organized around four questions: (1) What do we know for sure? (2) Based on this, what do we expect to happen in the future? (3) What tools can we give managers now and what tools are coming soon? (4) What needs to be done now?

## What We Know

The climate will change. Even short periods of climatic stability have been rare; so, there is no reason to expect the present apparently stable climate to continue indefinitely, even without human intervention. However, changes caused by human land use have been at least as important as any climate change. Furthermore, changes induced by changing climate may be difficult to distinguish from those caused by human land use patterns.

Because the need for data rises exponentially as the scale of a climate model becomes smaller,

we may never be able to predict local climate accurately at the scale at which land management treatments are applied. Furthermore, because there are elements of randomness and chaos in the behavior of ecosystems, there will always be an element of uncertainty in the outcome of any management activity.

The ecosystems and condition of the land today have changed and evolved over millions of years; but in the past 2,000 years, humans have influenced ecosystems greatly and changed the course of their evolution. In fact, it is difficult to find anything to study that has not been modified in some way by humans. Species respond individually to environmental changes, which changes community composition over time. Removal of species by extinction and introduction of exotic species, including plants, animals, insects, and microorganisms, are changing the composition and competitive interactions of many ecosystems.

The place to look for early signs of change is in the ecotones at biome boundaries. There, the vegetation already is under stress, and even small changes in climate or land use may cause the biome boundary to shift. Plant and animal communities and their associated ecosystems will continue to change both in response to climate changes and increasingly

from human use patterns. The responses can be very complex.

Human populations will continue to restrict and fragment natural ecosystems worldwide. As the U.S. population rises, especially in rural areas, private lands will continue to fragment into smaller ownerships, increasing the complexity of management on adjacent and nearby Forest Service lands.

## What We Can Expect

The past will not repeat itself exactly, even though the same forces and processes are driving the changes. However, we can estimate what and where future ecosystems will be if we can discern the trajectories that they are following now. Despite this, many ecosystems have been changed already by human intervention so much that they may not be able to respond to the coming climate and land use changes in the ways that they responded to climate change in the past.

Extremes are probably more important than means. Current climate models can describe expected changes in atmospheric CO<sub>2</sub>, temperature, and precipitation; but these are averages over large regions. However, these models also suggest that there will be more variability and more

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rapid change than has been experienced in the past. Species and ecosystems are likely to react more to major perturbations than to small changes in averages. Furthermore, beyond a certain threshold of change, a system may suddenly switch to a new and different stable state, perhaps irreversibly. This would be a very difficult phenomenon to anticipate.

A number of trends already in place will continue. Species have responded individually to environmental changes in the past and will continue to do so in the future. Nitrogen deposition will increase in association with highly populated areas. Ozone generation will increase in the troposphere and continue to decrease above the stratosphere, at least in the short term. The number and size of areas impacted by the introduction and establishment of exotic species will increase. This includes plants, animals, insects, and microorganisms. Fragmentation in ownership and land use patterns, and intensity of human use will increase. Human populations will continue to increase, including and perhaps especially in rural areas.

Given a warmer and possibly drier climate, fire models suggest that there will be a shift of the lower tree biome boundary up in elevation in the northern Rocky Mountains. Trees will be replaced by shrubs and forbes. Although ponderosa pine is well buffered against drought, genetic studies suggest that western larch would be adapted 700 m higher in elevation than where it is now, and may disappear from its lowest current elevations.

Warming in the Southwest is likely to cause a loss of site productivity. Conversion of ponderosa pine to pinyon-juniper would cause a 40% soil carbon loss; conversion to desert scrub would cause an 85% carbon loss.

Higher CO<sub>2</sub> levels, especially coupled with increased minimum temperatures, is unlikely to have an adverse impact on the cold hardiness of Rocky Mountain Douglas-fir or ponderosa pine.

Although higher CO<sub>2</sub>, warmer temperatures, and increased precipitation across the U.S. may increase wood production more in the North than in the South, the economics of forest products still favor the South. Stumpage prices are expected to decline, not rise, in real dollars.

### Management Tools

The following list illustrates the kinds of tools that are available to managers now or will be shortly. These are the items that were discussed at the Workshop, and not an exhaustive list. Inevitably, in a workshop of this size, not all disciplines are well represented; in this case we have little to say about wildlife and hydrology.

Many studies of the past tell us how the climate has changed, especially over the past 30,000 years, how ecosystems have changed in response, and more recently, how human land use has changed ecosystems. These include dendrochronology, palynology, the study of packrat middens, and historical records. By learning what changes have occurred in the past, we can better estimate how climate and ecosystems might change in the future.

Many models describe different aspects of climate and ecosystem behavior, and they are improving rapidly in their ability to describe the real world, to incorporate complexity, and to make accurate predictions. However, they still give only partial answers. The challenge to using these models effectively is to recognize the assumptions that are built into them and understand the limitations of the answers they give.

Establishing correlations between tree ring chronologies that identify drought years in the northern Great Plains and El Nino-Southern Oscillation events over the past 400 years may enable us to forecast droughts and severe fire seasons 6 months or more in advance, which would have considerable economic value. Weather forecasting models are increasingly able to predict El Nino events that far in advance.

The shape and posture of trees near timberline can be used to determine prevailing wind speed and direction, which, in turn, determines where the snowpacks will be. Much information can be obtained from these observations without the need to erect weather towers. In addition, tree ring growth at timberline is expected to be very sensitive to temperature increases which lengthen the growing season. (In the central Rockies, there is no indication, yet, of increased growth over the past few decades compared to previous years.)

Measurement of photosynthesis and stomatal conductance of alpine forbs is being explored as a way to determine which species may be most susceptible to air pollution and could be used as bio-indicators of air quality.

In order to observe a dynamic ecosystem and be able to detect changes and trends, we need multiple data points in time and space. An example is the chemistry of alpine lake water, which fluctuates greatly with season. One of the most valuable tools for detecting change is repeated measurement of permanent plots. This includes repeated photography, which is especially useful because it is not necessary to decide in advance what the important features of the landscape are.

### **What Needs To Be Done Now**

We know that change is inevitable, and we think we know its direction, at least at a global level; but we are much less certain about its direction and magnitude at a local level, the level at which managers must act. In the face of uncertainty, the prudent management philosophy would be to maintain resilient ecosystems that can adapt to change, whatever its direction. Some species that are rare now were abundant in the past; and we do not know which ones may become important in the future. Therefore, it is important to maintain those that we can. Structural complexity of the ecosystem will help. Where there is a choice, we should favor species that have a broad range of adaptation within local ecotypes. We may need to be prepared to move species whose habitat is disappearing, as might happen on isolated mountain tops, if the climate warms.

To know what is happening we need monitoring systems, but first we must decide what is

important to monitor. The extent and complexity of most ecosystems make it impossible to monitor everything, even in principle, and especially considering our limited resources. The Forest Service has done a good job of monitoring some of the economically important aspects of ecosystems, such as timber inventory and fire danger. This needs to be expanded to other features.

It is not possible to provide a "cookbook" solution. What needs to be monitored will vary by location, management goals, and changes identified by monitoring. However, several features will be common to many situations, including: (1) carbon fixation and accumulation, i.e., growth in relation to weather; (2) species composition; (3) the natural history in time and space of land use; and (4) the location of ecotones.

The monitoring system needs to be intensive enough in time and space not only to detect changes, but to allow determination of their cause in relation to the range of past variation. The better the monitoring system is, the sooner trends will be detected, the sooner management can take corrective action if needed, and the less likely it is that there will be an unstoppable ecological disaster.

It is imperative to keep good, consistent, long-term records. This is the core database of any monitoring.

The next step is to use the monitoring system as the control for adaptive management by evaluating the effects of management actions and noting departures from management intent. This would be the basis for revising plans for the next set of actions.

We must devise rapid-response managerial structures for ecosystem management. The Forest Service has been very successful at devising management structures for anticipating, preparing for, and responding to fires. The ecological disasters that might happen need similar attention, although they will not be as sudden and spectacular as fire.

In conclusion, to many managers and policy makers there may seem to be a lot of disagreement among scientists about what changes to expect in the future. At the cutting edge of science there always will be differences of opinion; but that should not obscure the broad consensus on matters about which we know a great deal. We know enough to say that change is inevitable, and that there are some specific actions that can be taken now, so that as these changes occur and in whatever direction they occur, they will be recognized, and we will be able to react effectively to them to maintain a productive world on which our existence and life styles depend.

# Climate Change from a Global Viewpoint<sup>1</sup>

Douglas G. Fox<sup>2</sup>

Human induced climate change can be viewed as yet another stress on ecosystems already dealing with a increasing set of human driven stresses. It is unlikely that the specifics of climate change will ever be sorted out from others, such as habitat fragmentation and air and water pollution.

In general, the most vulnerable ecosystems will be those whose sensitivity to change is great but for which adaptation options are limited, thus the less the management, the greater the potential vulnerability. Procedures to adapt to climate change in natural ecosystems are not well developed and are limited by human activities that fragment landscapes. Ecosystems "disrupted" by climate change may take many centuries to "recover", or if extinction of species is involved, may never "recover".

Global models predict the possible consequences of changing temperature and water availability on forests. Of the world's existing forested areas, 14-65% with a global mean of 34%, will

undergo major changes in vegetation type, which has major implications for commodity extraction and forest management, especially in tropical forests. Warming and elevated carbon dioxide are likely to increase the net primary productivity of unstressed temperate forests that are not nutrient-limited, but net carbon storage may not change much because of associated increases in soil respiration. Net primary productivity may increase while standing biomass may decrease due to the added stress of changes in species range, disturbance, and higher temperatures which will cause higher respiration. Because the maximum rate of carbon loss is greater than gain, significant amounts of carbon may be released to the atmosphere as a result of forest decline and readjustment.

It is likely that temperature change may not have much effect on rangeland, but changing amounts and seasonality of rainfall may, especially in the tropics. Increasing CO<sub>2</sub> is likely to reduce forage quality by increasing the C to N ratio. Drier growing seasons in temperate grasslands may favor shrub communities. It is likely that because of relatively tight coupling between rangeland type and climate, shifts in the climate will be accompanied by shifts in rangeland type boundaries. Tundra are expected to be sensi-

tive to warming. Arctic permafrost loss in a warmer global climate will increase methane and carbon release to the atmosphere.

It is likely that between 1/3 to 1/2 of all current mountain glaciers could disappear in the next 10 years. The reduced effect of glaciers and mountain snowpack will affect downstream hydrologically dependent systems, soil stability, and related economies. Species with climatic ranges limited to mountain tops may become extinct because their habitats will disappear.

Recreational industries dependent on current, stable climate may also suffer. Climate change could have a major impact on regional water supply and demand. Relatively small changes in temperature and precipitation can have large effects on runoff, particularly in arid and semi-arid areas. Climate models do not provide sufficient information for assistance in water management issues.

At the same time, sustainably managed forestry can play a role in reducing atmospheric concentrations of greenhouse gases, carbon dioxide, methane and nitrous oxide. Although there are considerable uncertainties and debate within scientific communities, expanding tree planting, aggressive agroforestry, and reduced deforestation are all positive influences.

<sup>1</sup>Paper presented at the Interior West Global Change Workshop, Fort Collins, CO, April 25-27, 1995. (Developed from Watson, et al. 1995, "Summary for Policy Makers—Impacts, Adaptation, and Mitigation; IPCC WG II Second Assessment Report").

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# 245 Wind and Ecosystem Response at the GLEES<sup>1</sup>

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**Abstract.**—Research was conducted to determine wind patterns and snow deposition at a high elevation alpine/subalpine ecotone site using deformation response of trees to prevailing winds. The research has provided detailed maps of wind speed, wind direction, and snow depth as determined from tree deformation. The effects of prevailing wind on tree blowdown at the site have also been described. This research is an example of interaction of biological and physical scientists working together to provide detailed description of an ecosystem response to the atmospheric environment.

## Introduction

High elevation ecosystems are particularly vulnerable to atmospheric deposition and climatic change. These ecosystems are already highly stressed, and they experience environmental extremes which make plant survival difficult. They commonly experience extremely low temperature, with frosts likely to occur anytime during the growing season. They also experience moisture stress, particularly after snowmelt, because of the low moisture holding capacity of the relatively young and shallow soils. Soils are also low in CEC, and nutrient supply for growth is low. Nevertheless, many plants species have adapted to these harsh environments, and survive from year to year. Most of the vascular plant species occurring at these sites are perennial and rely on root reserves to survive especially difficult years.

<sup>1</sup>Paper presented at the Interior West Global Change Workshop, April 25-27, 1995, Fort Collins, CO.

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The research described here was conducted at the Glacier Lakes Ecosystem Experiments Site (GLEES) in the Snowy Range of SE Wyoming (Musselman 1994). The site is a 600 ha alpine/subalpine ecotone watershed where research is conducted on atmospheric deposition effects on terrestrial and aquatic components of the ecosystem. The research site is located on the SE side of the Snowy Range Ridge. It is located at about 3400 m elevation, and is subject to strong, westerly, prevailing winds (Musselman 1994). Tree asymmetric deformation from wind is common at the site (Wooldridge *et al.* 1995a). Tree deformation occurs when blowing surface ice crystals erode tree needle epidermal tissue so that they are subject to desiccation and death. The result is survival of tree needles only on the downwind, lee side of the trees, and subsequent asymmetric growth of tree foliage and branches. Tree blowdown is common in certain areas of the GLEES, particularly in the eastern portion of the watershed. There is a definite directional pattern in the orientation of the downed trees.

## Methods

We examined the degree of tree deformation from wind, and the direction of the deformation, to construct detailed maps of climatic wind speed, wind direction, and snow depth for the research site (Wooldridge *et al.* 1995a). A 300 ha portion of the watershed was divided in 100 m grids, with trees assayed at each grid corner. A smaller portion of the watershed (30 ha) was surveyed at a 50 m grid scale. Wind direction was measured by compass direction of the tree deformation of an Engelmann spruce (*Picea engelmannii*) or subalpine fir (*Abies lasiocarpa*) tree sampled at each grid corner. Wind speed was determined from the empirical relationship between amount of the tree deformation and the mean wind speed. Tree deformation was determined by two methods. The first classified deformation visually on a scale of 0-8, with 0 indicating no deformation and 8 indicating a full krummholz mat. The second method calculated deformation from photographs taken at right angles to the bending, with angle of bending used to determine the wind speed. Empirical equations were used calculate wind speed

based on the deformation (Hewson *et al.* 1979; Wade and Hewson 1979). Wind speed was mapped on a 100 m grid or smaller map scale for the research site. The wind speed, wind direction, and snow depth maps were verified by long-term meteorological measurements taken at the site.

Snow depth was mapped based on 1) lack of deformation indicating snow cover protection from wind damage, or 2) presence of brown felt blight (*Herpotrichia juniperi*) damage indicating long-term snow cover. The height that deformation began on the trees, and the height that brown felt blight ended, was recorded at each grid point. Isopleths of wind speed and snow depth and wind speed were drawn from the map grid data.

A separate study examined direction of tree blowdown in relation to wind direction (Wooldridge *et al.* 1995b). Tree blowdown direction was determined by measuring compass bearing of downed trees on the ground, or orientation of downed trees on aerial photos. This information was related to wind speed and direction data. Prevailing wind direction was determined from the tree deformation study and from snowdrift patterns on aerial photos.

## Results

These measurements demonstrated that in the local upper treeline landscape, spatial information on climatic wind speed, wind direction, and snow depth can be determined from tree deformation. Detailed climatic maps have been constructed from

the data (Wooldridge *et al.* 1995a). The research also demonstrated that windthrow of trees at the site can be explained by the downslope high speed winds from the northwest or prevailing winds from the west (Wooldridge *et al.* 1995b).

Wind speed and wind direction varied at the site, dependent on terrain features. The climatic mean wind speed at the study site was 7.4 m s<sup>-1</sup> as determined from tree deformation. Mean annual wind speed from the meteorological tower at the site, using a standard anemometer, was 7.8 m s<sup>-1</sup>. The tower is at a location indicating an 8.0 m s<sup>-1</sup> annual mean wind speed from tree deformation data. The two methods of determining wind speed (Hewson *et al.* 1979; Wade and Hewson 1979) provided estimates that were not significantly different. This study provided data for construction of a wind speed map for the site at a surface grid scale of 100 m or less resolution.

Wind direction is primarily westerly at the site, as indicated from the tree deformation and the meteorological tower wind vane. The tree deformation indicators located small scale terrain channelling, and some upwind divergence and downwind convergence around terrain obstacles.

Snow drift orientation was also useful to corroborate prevailing wind directions, and were consistent from year to year as determined from aerial photographs. They indicated a channeling of wind along the SE side of the Snowy Range Ridge, moving in a NE direction. In addition, winds moved from the NW over the crest of the ridge. NW to SE drifting was evident on the top of

the ridge, and further SE of the GLEES research site. Drifting within the lee of the ridge indicated SW to NE channelling. A detailed map of wind direction at a scale of less than 100 m surface area was constructed for the GLEES from tree deformation data and from snow drifting patterns.

Isopleths of snow depth constructed from biotic indicators of tree deformation and brown felt blight showed a wide variation in depth, depending upon terrain features and exposure. Snow depth ranged from less than 0.2 m to 5.3 m as estimated from tree symmetry and brown felt blight. Shallow accumulations were found on exposed ridge tops and hills, and over the lakes where wind speeds are high. Mean snow depth for the East Glacier catchment portion of the site was 2.0 m as determined from the biotic indicators (Wooldridge *et al.* 1995a). A snow survey at the site indicated a mean snow depth of 2.6 m for 1991 (Sommerfeld *et al.* 1991). Lower snow depth obtained from biotic indicators than that obtained from the systematic snow survey occurred as predicted. Thus, to obtain accurate estimates of snow depth, biotic indicators of snow depth must be adjusted up by about 20-25%.

Tree blowdown indicated a bimodal direction for windthrown. The bimodal peaks of approximately 265 and 310 degrees, correspond to (1) the prevailing westerly winds and (2) gusts > 20 m s<sup>-1</sup> from over the main southwest to northeast quartzite ridge of the Snowy Range. Most blowdown appeared to be from the downslope gusts,

with slightly lesser amounts of blowdown from the prevailing winds. Fewer than 10% of the trees were downed in directions outside of 220 to 360 degrees.

## Discussion and Conclusions

This study provided for the construction of detailed wind speed, wind direction, and snow depth maps of the research site. The maps provide information at a surface area scale of 100 m or less. The data provide a cost effective and accurate measure of long-term wind patterns at the site, and provided important information to explain ecosystem response to these meteorological patterns. The study provided detailed microsite wind speed data and prevailing wind information for the research area not possible from the one meteorological station located at the site. The maps help describe microclimatic conditions and resulting vegetative habitat at a small scale at the site. They have been used to model tree invasions into meadows at the upper treeline ecotone (Moir and Lee 1990).

The direction of the tree deformation is an indication of the prevailing winds, particularly those which occur in winter when the trees are most subject to desiccation. Meteorological tower data at the site indicate that winds speeds are higher in the winter, although prevailing winds are WNW year round. The study demonstrated the important influence of terrain on wind direction and local channelling from small terrain features.

The tree deformation indicator of wind speed provided an

estimate of mean annual wind speed at the site. The tree indicators will integrate effects of desiccation, with desiccation in years of high wind speeds, but regrowth upwind in years with lower wind speeds. The Griggs-Putnam index (Hewson *et al.* 1979) and the Wade and Hewson (1979) methods provided similar estimates of wind speed. Since the Griggs-Putnam method is quicker and easier to use, it can be used directly in the field, and provides estimates of wind speed at a scale not possible from weather stations. Data from a meteorological station at the GLEES indicated that the method provides reasonable estimates of mean annual wind speed. It is the method of choice for estimation of wind speed in the absence of meteorological data.

The snow depth indicator by tree deformation is an estimate of the annual snow accumulation in low snowfall years. Thus, it will underestimate mean annual snow accumulation. The height that deformation begins is at the snow surface. The highest concentration of wind blown ice crystals occur a few cm above the snow surface, causing desiccation and death in this surface layer. In low snowfall years, this desiccation will be lower on the tree. Since growth does not reoccur on these lower portions of the tree, the height of the deformation is an indication of the low snowfall year snowdepths.

Brownfelt blight causes death of coniferous foliage when the foliage is under snowcover for a long period of time. Thus, brown felt blight would be an indicator of high snowfall years when snowdepth is deep and long

lasting. However, brown felt blight was less useful as an indicator, since its occurrence was infrequent throughout the site.

The research indicates that topography has a major effect on wind speed, wind direction, and snow depth at the site. Snow depth is a good indicator of amount of atmospheric deposition. Areas of deeper snow accumulation will have higher chemical deposition, since snow has an associated chemical component. In addition, physical and micro-environmental factors which favor snow accumulation, such as areas of low turbulence causing settling, will also favor deposition of the larger particulate portion of dry deposition. Thus, areas where there is more snow deposition are areas with larger amounts of wet and dry chemical deposition.

The areas with the deepest snow accumulation often have snow cover lasting longer into the growing season. Examination of habitat characteristics at the research site studied here indicate that wind, through its effect on tree deformation and tree blowdown, has an important effect on these ecosystems. Wind, in association with terrain features, also has a major influence on snow accumulation. The snow accumulation and associated chemical deposition and snow-melt duration, in turn, have a major influence on the adaptation and survival of plants, the distribution of plant communities, and the resultant vegetative habitats which occur in each area of the study site.

The bimodal pattern of tree blowdown at the site was explained by the direction of the

prevailing winds and wind gusts. The blowdown has implications for tree survival in this ecosystem, and the vegetative habitats which occur at these sites.

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# Spatial Extrapolation and Forecast Uncertainty of Three Simulation Models for Ponderosa Pine along the Front Range of Colorado<sup>1</sup>

Michael Arbaugh<sup>2</sup>

**Abstract.**—Three forest simulation models, GenGym, Zelig, and Forest-BGC, were used to examine the ability of models to spatially extrapolate forest information to new sites, and forecast results into the future. The models were able to simulate cumulative carbon when using all information, but models consistently underestimated bole carbon when spatially extrapolated. Site fitted simulations were more accurate and precise for cumulative carbon than forecasts from spatial extrapolations. Forest-BGC simulated annual dynamics more accurately than other models; but GenGym forecasted mean cumulative carbon within 2% of the calculated values at the end of the period. Model prediction ability for this study was a function of the adequacy of data used for parameterization, and the scale of interest.

## Introduction

Although many studies have been conducted to examine the effects of climate change on forest development there has been little work conducted on the reliability of these estimates. The assumption that models are generally reliable (i.e. model simulations reflect actual differences in system behavior) are based upon model ability to simulate relevant biological processes, and the ability to fit data during the time before the scenario period.

There is, however, little work to support these assumptions for most quantitative vegetation simulation models. Recent work by Oreskes et al. (1994) argues that the methods for determining model verification and validation result in over-optimistic estimates of model performance for hydrological and geological simulation models. Their arguments are equally applicable to vegetation

models. Some of their arguments are supported by Ryan et al. (1994a,b) who examined the ability of six carbon flow models to simulate two forest systems over a 20-year period. Carbon flow models were found to be inconsistent predictors of carbon accumulation, and had large errors for some processes such as nitrogen cycling.

In this study bolewood carbon estimates developed from 30 sites was used to examine spatial extrapolation and forecasting abilities of three simulation models. Two different parameterizations were used with three models (GenGym, Zelig and Forest-BGC) to simulate ponderosa pine (*Pinus ponderosa*) forest growth along the Front Range of Colorado to determine the ability of models to spatially extrapolate information to other locations, and to forecast model results into the future.

## Methods

In the first parameterization, information from 5 sites were used to develop model parame-

ters that were extrapolated to the remaining 25 sites. The second scenario used information at each site to develop individual site parameterizations. Differences in the accuracy and precision between the two parameterization approaches for bole carbon accumulation was used to examine the error associated with spatial extrapolation, and sources of error for the extrapolations.

Both parameterizations were then forecasted over a 44-year period at 30 sites to determine if interactions between spatial extrapolation and forecasting result in larger uncertainty than forecasting from models fitted to individual sites.

Three models, GenGym (Edminster et al. 1991), Zelig (Smith and Urban 1988) and Forest-BGC (Running and Coughlan 1988), with different modeling approaches were used to determine the role of model approach for spatial and forecast accuracy and precision. Each model represents a different philosophical approach to describing forest systems, and all were used in previous studies of forest systems in

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the Rocky Mountains. Two models, GenGym and Forest-BGC, were used in previous studies of ponderosa pine forests in the Rocky Mountains.

## Comparison Information

Data from 700 tree-ring series, 150 density plots, soil and needle combustion analysis, bark thickness and mortality plots were used to construct annual and cumulative bole carbon changes at 30 sites of ponderosa pine between 1900 and 1988.

Stand structure and age varied considerably between the sites. Densities ranged from 253 to 2466 trees per hectare and woody biomass from 28 kg/ha to 96 kg/ha in 1988. Mean diameter of sample trees ranged from 23.5 to 41.3 cm, and mean height ranged from 10 to 19 m. Average tree age varied between 67 and 146 years, with the majority of stands less than 100 years in age. More than 70% of trees were established during settlement and post-settlement periods. Ponderosa pine comprised over 80% of the stand basal area in all stands, the remainder consisting of Douglas fir (*Pseudotsuga menziesii*) and quaking aspen (*Populus tremuloides*).

## Climate information

Daily climate information was collected from 17 stations located in the mountain and adjacent cites along the Front Range. Averages of the five closest weather stations to each sample site were used to estimate climate for the site. Daily temperature

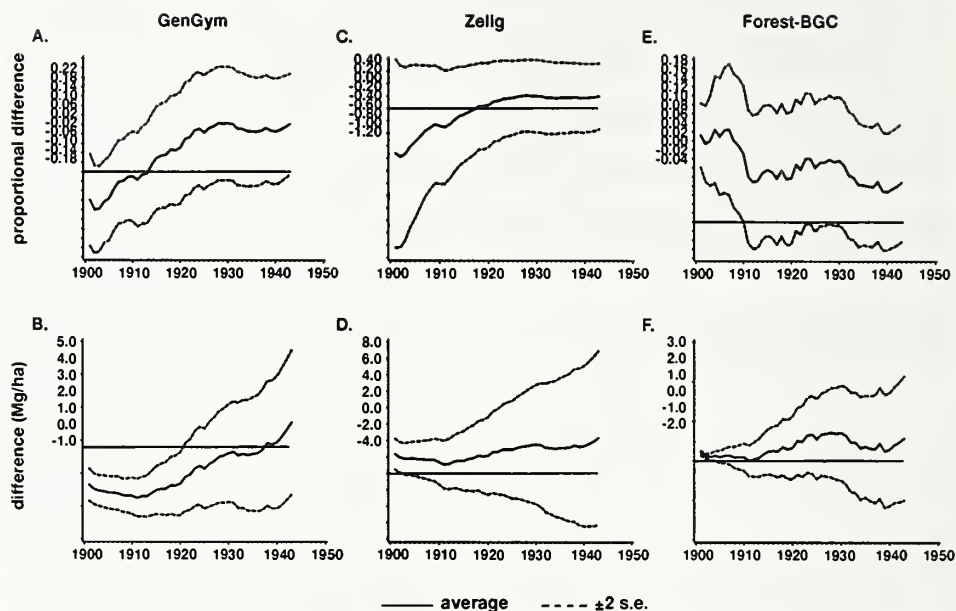


Figure 1.—Average differences (observed - simulated) and proportional differences (differences / observed) for the three models for spatially extrapolated parameterizations from 1900 through 1943. Dashed lines are 2 standard error lines ( $n=25$ ).

records were adjusted for elevation differences before averaging. Precipitation values were not adjusted before averaging. Missing values for both temperature and precipitation were estimated using standard meteorological techniques prior to averaging.

## Results and Discussion

Average differences (data - simulation) and proportional differences (differences/data) of cumulative carbon (fig. 1) indicated that spatial simulation differences were proportional to cumulative carbon for all models, resulting in increasing standard errors through time for spatial extrapolations; GenGym and Forest-BGC both had standard errors of approximately 2%-3%, while Zelig standard errors were about 5%-6% of the average at the end of the period.

The similarity in results for spatial extrapolation indicates that parameterization data was the most important factor for model results. Examination of correlations between site attributes and ending carbon differences indicated that spatial extrapolation results were because of the tuning sites selected. Tuning sites were selected *a priori* to represent extremes in density, topography and latitude. The set did not include older sites, which was an important determinant of carbon accretion patterns. The lack of older sites among the parameterization data resulted in overestimation of cumulative carbon by spatial simulations for older sites, because older sites did not have increasing accretion patterns present in younger sites.

The contrast between spatial extrapolations and site fitted simulations (using all data) also supported the importance of data for simulation results. Site fitted

simulations followed individual and averaged data trends closely for all models. Average differences were much smaller than spatial extrapolations, and uncertainty intervals were constant through time rather than proportional (fig. 2). Thus with sufficient data all models were adequate to simulate regional cumulative carbon. Correlations between differences and age were not significant for two models, only GenGym differences still being associated with site age.

Forecasted spatial and site fitted simulations differed greatly in accuracy and precision. Spatial forecasts for GenGym and Forest-BGC underestimated cumulative bole carbon in 17 of 25 sites by 1988. Zelig estimates were more balanced, underestimating 11 sites and overestimating 12, however underestimates were often more extreme.

Spatial extrapolations underestimated mean cumulative carbon for all models. Poorer fits were

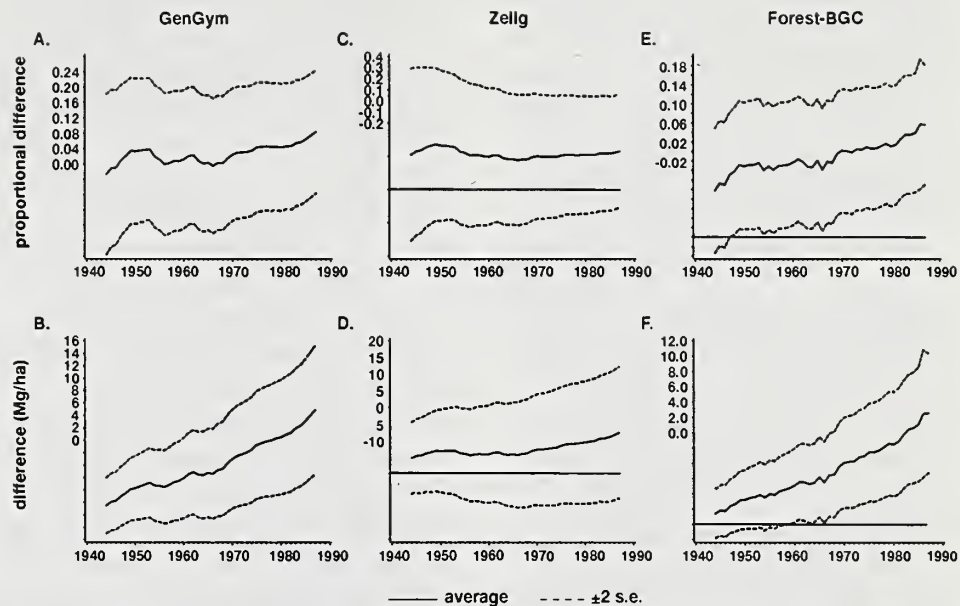


Figure 3.—Average differences (observed - simulated) and proportional differences (differences / observed) for the three models for forecasts of spatially extrapolated parameterizations from 1944 through 1987. Dashed lines are 2 standard error lines ( $n=25$ ).

because of continued overestimation of cumulative carbon for older sites, and sites with larger basal areas (fig. 3).

Models had distinct cumulative carbon patterns when site fitted simulations were forecasted

(fig. 4). Zelig and GenGym had relatively constant proportional differences through time, while Forest-BGC had increasing proportional differences through time. GenGym was within 2% of the calculated values, while Forest-BGC underestimated by 4%, and Zelig overestimated by about 10% by 1987. Model uncertainty increased proportionally through time for all models for both types of parameterizations, but the proportions differed among the models.

Differences between patterns for site fitted simulations imply that model approach may influence long-term model behavior. Examination of Forest-BGC indicated that differences in forecast trends was because of the lack of explicit growth limits, such as maximum height, diameter and site indices in Forest-BGC that limit growth for Zelig and GenGym. In the absence of growth limiting functions error

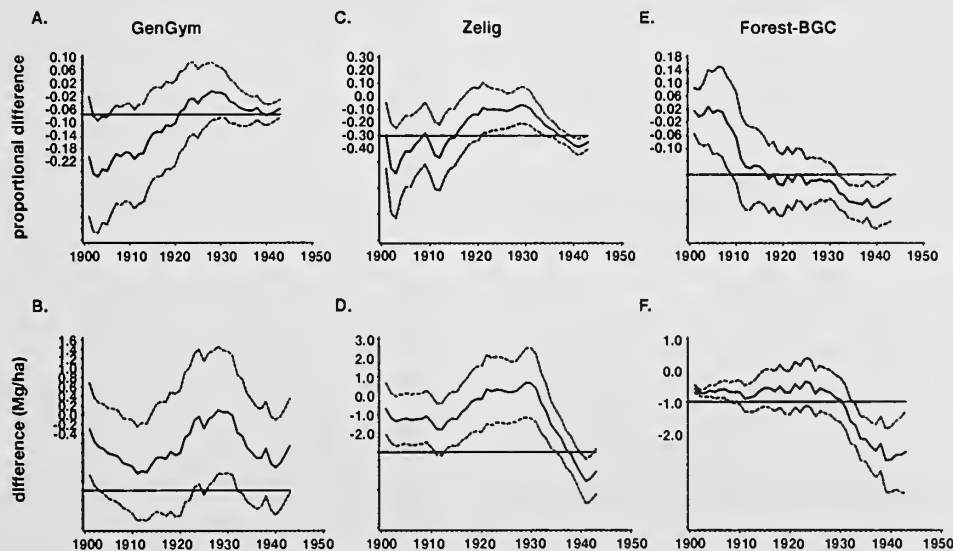


Figure 2.—Average differences (observed - simulated) and proportional differences (differences / observed) for the three models for site fitted parameterizations from 1900 through 1943. Dashed lines are 2 standard error lines ( $n=30$ ).

accumulated through time that resulted in increased divergence from calculated values.

Neither spatial nor site parameterizations were accurate predictors of annual fluctuations in carbon accumulation, however patterns of simulated fluctuations by Forest-BGC were very similar to calculated patterns. The lack of mechanisms to simulate previous year weather effects on bud primordia and carbohydrate storage probably resulted in the slightly lagged relationship of fluctuations. Inclusion of past climate effects has increased the model fit with annual carbon gain for Forest-BGC in previous studies (Graybill and Rose 1992; Hunt et al. 1991) of ponderosa pine in the Rocky Mountains.

Instead, the results may indicate that scales of model application are important for model reliability. Organizing models by scales of intended results makes the observed differences more

consistent with expectations. Forest-BGC was originally developed to simulate hydrological and carbon accumulation dynamics for short (1 to 5 year) periods. Detailed mechanistic linkages enable it to calculate annual dynamics of carbon accumulation, nitrogen and hydrological budgets. Thus annual carbon prediction and cumulative carbon precision for individual sites should be expected. At larger scales GenGym should perform best, as it is the model applied nearest to its intended scale of 20 to 200 years. The lack of accuracy by Zelig is also understandable, since it is intended for time scales associated with forest succession. At long time spans it is less important that stand productivity be accurately simulated, than correct portrayal of species replacement dynamics be simulated.

## Conclusions

Accuracy of spatial extrapolations appears to depend on the numbers of sites and the criteria used to select sites. Increasing the number of sites should result in more accurate estimates by including a larger range of variation for model parameterization. Better selection criteria may also increase accuracy of spatial extrapolations, however, it is difficult *a priori* to determine either the number of sites that is adequate, or the correct criteria for site selection.

The comparable fit of GenGym with other models indicates that young ponderosa pine forests may be less sensitive to climate fluctuations than more mesic forests. This is likely because of high water use efficiency and low maximum photosynthesis rates of ponderosa pine along the Front Range (Monson and Grant 1989). This forest type is likely resistant to rapid changes in species composition because of the direct effects of increased drought stress. It is more likely that forest changes will result from increased numbers of severe fires, insect outbreaks and reduced regeneration rates that result from increased biomass production and slow decomposition rates.

Neither spatial extrapolations from a few sites, nor individual site fitting was completely reliable as a modeling approach for forecasting forest change. Spatial extrapolation forecasts were biased by the small number of sites used for model development, regardless of the model used. Site fitted simulations were more accurate, but may have suffered from overfitting.

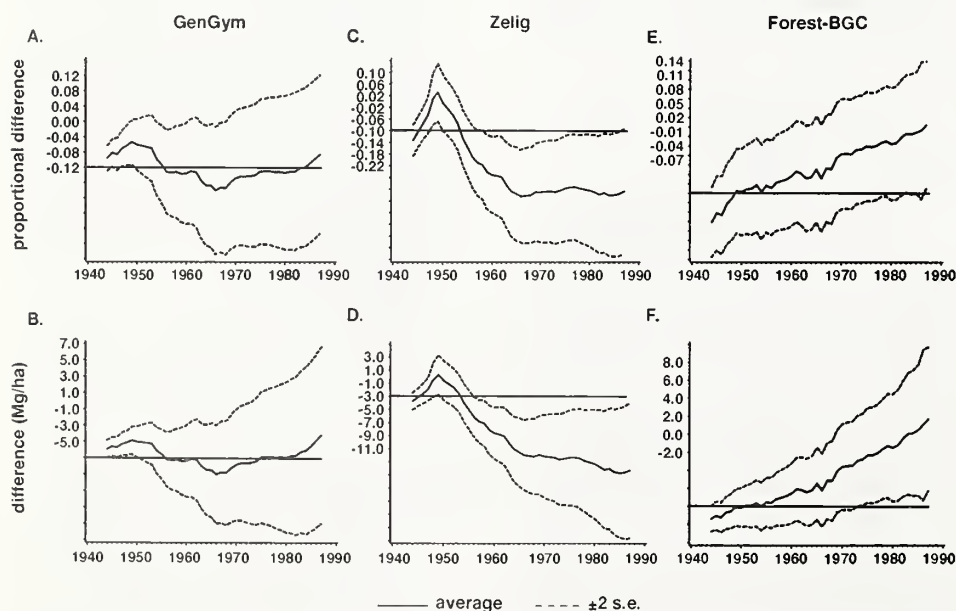


Figure 4.—Average differences (observed - simulated) and proportional differences (differences / observed) for the three models for forecasted site fitted parameterizations from 1944 through 1987. Dashed lines are 2 standard error lines ( $n=30$ ).

Inclusion of functional physiological relationships in the model resulted in better estimates of annual carbon accumulation, but not for cumulative carbon. This indicates that models including more detailed physiological relationships may result in more accurate estimates of short-term processes in forests, but may not increase predictive ability for long-term patterns. At longer time scales physiological relationships may not be as important as interactions between trees and site factors that limit total production.

Different model philosophies had varying levels of prediction accuracy and uncertainty. The patterns of model differences are consistent with differences in the intended scale of model application, but not with differences in model philosophy (Sharpe and Rykiel 1991). Forecasts of spatial extrapolations were less influenced by the model chosen than the data used, supporting the contentions of Oreskes et al. (1994), however site fitted simulations differed in predictive ability according to model approach.

Despite the problems and deficiencies of the models examined in this study, potential simulation model accuracy is high and uncertainty low if adequate data are used to develop model parameterizations. Site specific parameterizations of GenGym and Forest-BGC were within 4% of the calculated cumulative carbon values after 44 years. Forest-BGC uncertainty intervals were also less than 5% at the end of the period, which was comparable with the uncertainty of the calculated estimates. Further development of models and data requirements should

increase the applicability and reliability of models presently used in management and ecological studies of vegetation change.

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# Climate Change and Plant Species Responses over the Quaternary: Implications for Ecosystem Management<sup>1</sup>

Robin J. Tausch<sup>2</sup>, Cheryl L. Nowak<sup>2</sup>, and Robert S. Nowak<sup>3</sup>

## Introduction

Throughout the biosphere many changes to ecosystems have been recorded over the past 200 years. Ecosystem Management, basically, is a response to these changes that reflect an increased emphasis on maintaining their sustainability. We have, however, a limited understanding of how ecosystems function over the long-term because we have been looking at them in a fragmented fashion over the short-term. With our increasing awareness of the need for long-term sustainability of ecosystems we are becoming more aware of, and focusing more on, the dangers of fragmenting ecosystem structures and disrupting the natural processes within them.

A major part of why ecosystems occur, and behave as they do, is rooted in their long-term history of

development through the past two and a half million years of the Quaternary (Davis 1989, Foster et al. 1990, Tausch et al. 1993a). The Quaternary combines the Pleistocene from about 12,000 B.P. (before present) to over 2,000,000 B.P. and the Holocene from about 12,000 B.P. to the present. Climate during the Quaternary has been highly variable with an estimated 17 to 20 cycles of glacial advance and retreat (Tausch et al. 1993a, 1993b, van Donk 1976, Winograd et al. 1992).

Throughout the Quaternary the climate has been primarily glacial, with interglacials such as the past 10,000 years, being the average for only about ten percent of the period (Schoonmaker and Foster 1991). Plant species have responded individually to these cycles, resulting in a continual change in the species composition of plant communities (Foster et al. 1990). Paleoecological information clearly shows that communities and ecosystems are far less stable than we have assumed during our management activities over the past several decades. Pleistocene climate changes have also had major influences on plant evolution as species responded through adaptation, migration, or some combination of adaptation and

migration (Bradshaw and McNeilly 1991, Nowak et al. 1994a, Tausch et al. 1993a). Analysis of past vegetation change or stasis, during past climatic oscillations is proving to be one of our most productive methods to help us understand current and future ecosystem changes.

## Paleoecological History and Ecosystem Function

Our most detailed paleoecological knowledge of plant and community responses to past climate changes is available over the past 10 to 30 thousand years. These data come from studies of both pollen cores from lakes and swamps and from plant macrofossils retrieved from woodrat middens (Schoonmaker and Foster 1989, Betancourt et al. 1990). Regardless of location, paleoecological studies consistently show that communities and ecosystems are unique at each location and transient over time. These systems can be regional in extent and exist across a landscape, rather than a more dissected site by site basis. Ecosystems are both dynamic and pluralistic in nature and function across the landscape as a mosaic of dynamic processes. They are subject to the presence of thresh-

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olds and can change rapidly in response to small environmental changes if these thresholds are crossed (Laycock 1991, Tausch et al. 1993a). Such changes can be essentially permanent (Tausch et

al. 1994). It is increasingly clear that to understand why current communities appear as they are, and why they are changing as they are, knowledge of how they

came to be is as important as the knowledge of their current status.

## Great Basin Paleoecology

Our woodrat midden studies for northwestern Nevada have provided detailed information on the vegetation changes over the past 30,000 years (Nowak et al. 1994a, 1994b). These results indicate plant species have responded to the past climate changes in the Great Basin in three general patterns. First, some species have migrated regionally over large distances. Analogously, this has been the most common plant response in eastern North America (Webb 1987). For example, singleleaf pinyon (*Pinus monophylla*) has shown this type of response in the Great Basin (fig. 1). Second, other species identified in our midden macrofossils have migrated elevational-ly but largely remained in the same general region (figures 5 and 6 in Nowak et al. 1994a). Finally, there are species in our Great Basin studies that have remained relatively in place on some locations for most of the past 30,000 years, illustrated by Utah juniper (*Juniperus osteosperma*).

Because of the observed differences in response to past climate changes by individual plant species, community composition in the northwestern Great Basin, like those in studies from other areas, have been continually changing. These patterns of vegetation change over the past 30,000 years are illustrated by a classification analysis (fig. 2) of our midden macrofossil data (Nowak et al. 1994b). There are five primary

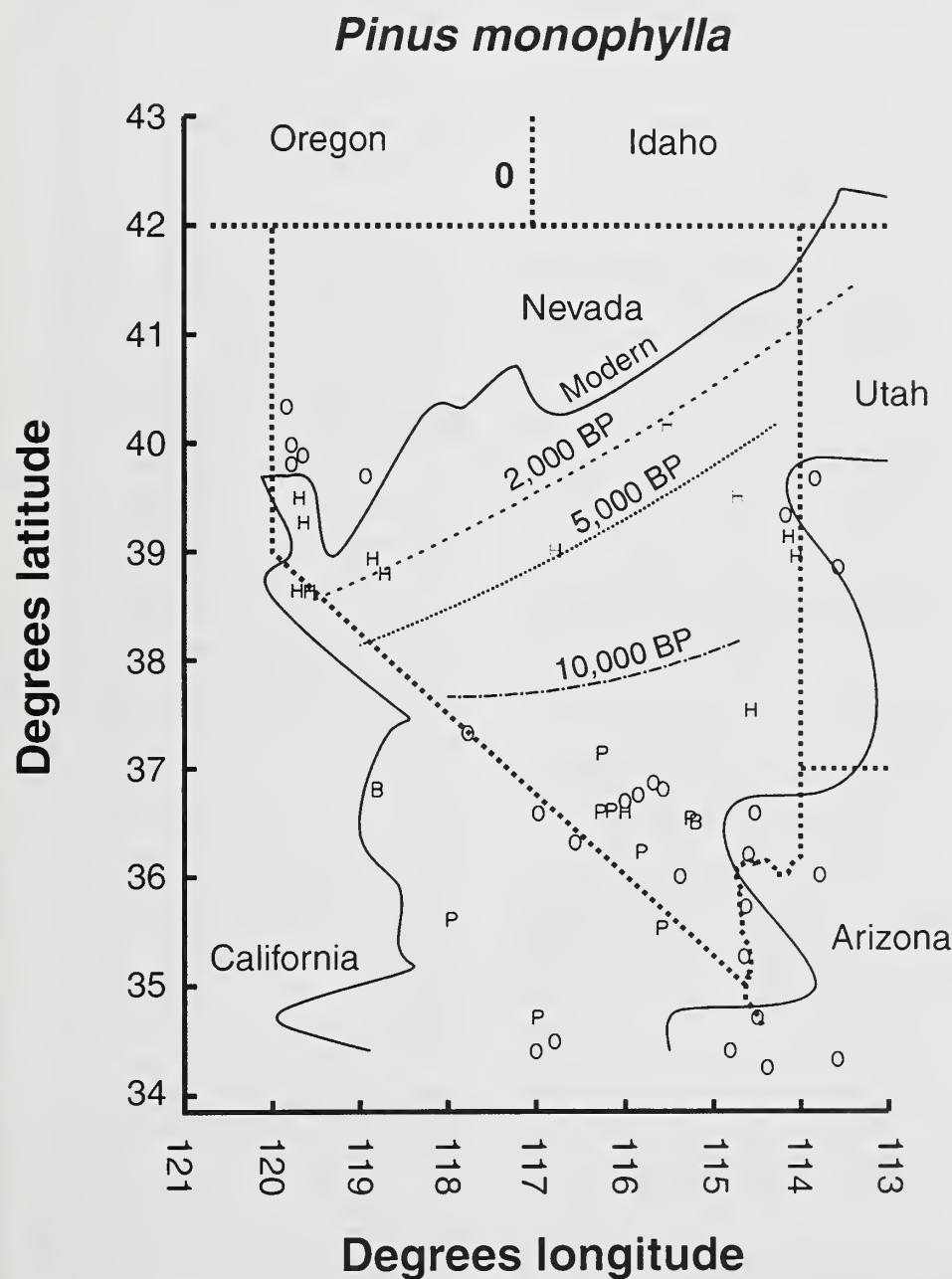


Figure 1.—Expansion of the geographic range of singleleaf pinyon (*Pinus monophylla*) across the Great Basin during the Holocene. "P" denotes Pleistocene fossil occurrences. "H" denotes Holocene fossil occurrences. "B" denotes both Pleistocene and Holocene fossil occurrences. "O" denotes fossil middens that did not contain pinyon. The bold line denotes the modern northern Geographic limit of singleleaf pinyon.

groups of midden samples identified over the 30,000 years that coincide with the patterns of documented past climate change. From 30,000 to nearly 12,000 B.P. there was a cycling between two groups of plant species, one occurring during more ice dominated periods and one occurring during less ice dominated periods of the Pleistocene. During the transition from the glacial climate of the Pleistocene into the interglacial

climate of the Holocene (about 13,000 to about 10,000 years B.P.), communities in northwestern Nevada went through changes that were rapid and largely directional. Over this transition plant species groups changed from one of the two that were dominant in the Pleistocene, through two transitional groups, to an assemblage representative of most of the Holocene (Nowak et al. 1994b). The Holocene group was the most

variable in species composition of all the groups identified over the past 30,000 years. Pleistocene communities also had a higher abundance of grass and forb species than Holocene communities where the abundance of shrub species is higher.

## Environmental Change and Plant Adaptation

Juniper is a conspicuous example of the type of species in northwestern Nevada that shows the ability to remain in place by apparently adapting to climate change (figure 2 in Nowak et al. 1994b). On one site on the west side of Pyramid Lake, Nevada, juniper co-occurs with whitebark pine twice during the Pleistocene. On this site during the Holocene juniper co-occurs with shadscale. These results illustrate the wide range of differences in climate that juniper was able to adapt to in the past. In addition, other shrub and grass species in the midden record show similar patterns, indicating this ability to adapt to changes in climate is common in the Great Basin.

Two species of juniper are present in the western Great Basin. These are western juniper (*J. occidentalis*) located in the Sierra Nevada, northwestern California, southeastern Oregon, and southwestern Idaho; and Utah juniper (*J. osteosperma*) located in the Great Basin of Nevada and Utah. A joint effort between the Reno lab of the Intermountain Research Station and the Environmental and Resource Sciences Department of the University of Nevada, Reno has recently begun to study the

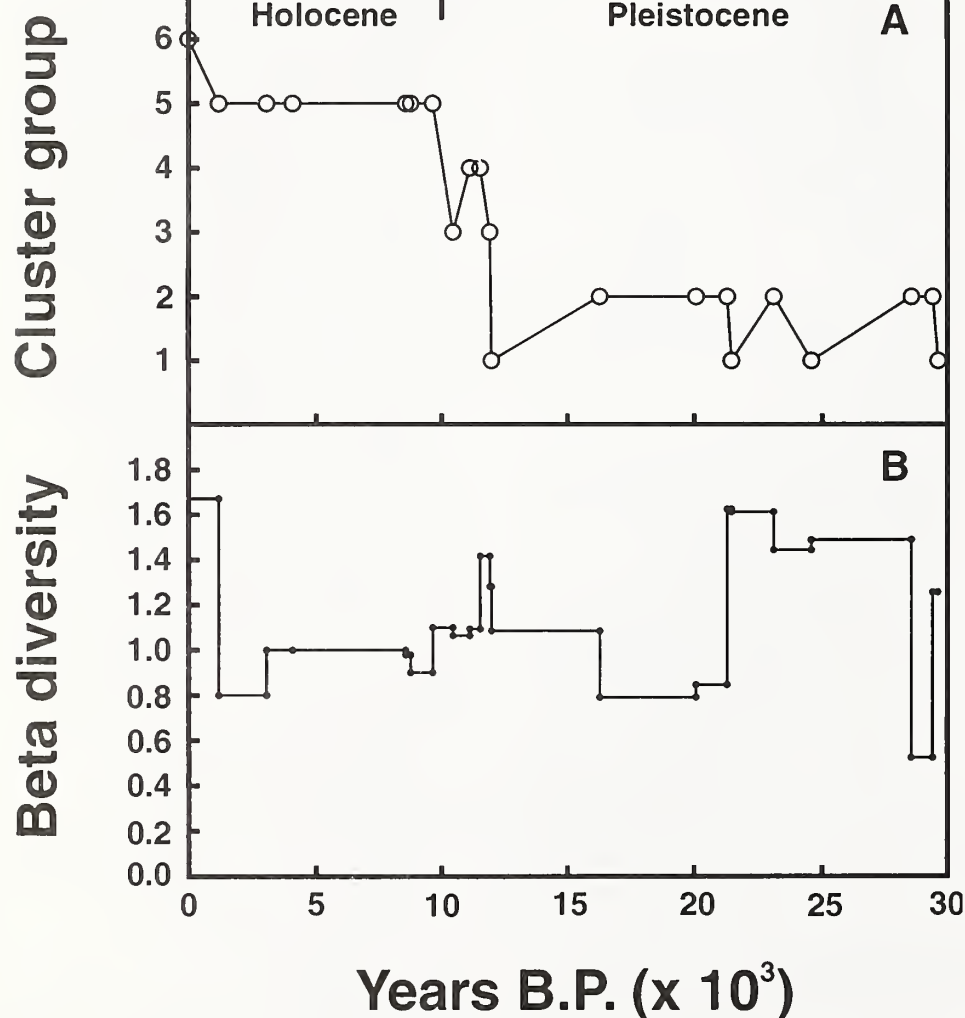


Figure 2. A.—Classification analysis of species assemblages for individual midden strata based upon cluster analysis. B. Beta diversity between contiguous pairs of vegetation assemblages for individual midden strata. Dashed lines are used to connect modern vegetation surveys with the youngest midden strata because the two vegetation samples are not equivalent.

ecophysiology and genetics of juniper across the Great Basin. These studies are designed to increase our understanding of juniper's ability to adapt to wide variation in climate. As a part of this study we have identified several locations within the Great Basin demonstrating that the adaptability of juniper that was evident in the past still exists today. We have mapped sites where juniper is growing in association with *shadscale* (*Atriplex confertifolia*) and joshua tree (*Yucca brevifolia*), or limber pine (*Pinus flexilis*), or bristlecone pine (*P. longeva*). All these locations are well outside the distribution of western juniper previously identified by taxonomists.

As a part of our expanded studies of juniper we have been cooperating with Dr. Paul Keim of Northern Arizona University on developing techniques for the DNA fingerprinting of juniper. Results from these preliminary genetic studies have indicated that the adaptability of juniper to past climate change has apparently been facilitated through hybridization between western and Utah juniper (unpublished data). Past climate changes and plant species migrations associated with the Quaternary apparently have resulted in repeated episodes of introgression between the two juniper species. Genetic evidence of this introgression is present as far east as central Nevada where localized occurrences of western juniper have been recently documented (Charlet in press).

The spatial pattern of introgression in juniper indicates it is more prevalent in areas of the northern Great Basin that are located to the

east of the former or pluvial Lake Lahontan. This lake periodically covered large areas of western Nevada during the Pleistocene (Morrison 1991). Studies have shown that the presence of this lake would have resulted in a significant lake-effect increase in precipitation which would extend to the east across north central Nevada (Hostetler et al. 1994). This increase in available moisture apparently permitted the eastward migration of western juniper, possibly several times during the Pleistocene. A woodrat midden collected on the east side of the present dry Winnemucca Lake, which was part of Lake Lahontan, dates to the late Pleistocene, and contains western juniper (Thompson et al. 1986). Our woodrat midden studies are being expanded into this area of the Great Basin to better document past examples of these patterns.

### Application to Present and Future Management

Paleoecological evidence clearly shows, plant communities really represent trajectories of change from the past, through the present, and into the future. The patterns and rates of these changes vary in both time and space. The community or ecosystem present at any point in time is first the product of the species present or in the process of migrating into the area. Second, these species interact with each other and with the sequence of environmental changes and disturbances that occur as the ecosystem develops over time. Management over the past sever-

al decades has ostensibly been to achieve a particular 'state' for each community and location of interest. In reality what we have been managing are trajectories of change because any 'state' is temporary in ecological time. The concepts of both habitat type and condition and trend, as applied in the past, are insufficient to meet current and future challenges (Tausch et al. 1993b).

Two categories of impacts are caused by current human activities, indirect and direct. Indirect impacts are generally continental to global in extent and are affecting every ecosystem on earth in some way. Because they occur over such large areas, and because their sources can be global, they are essentially not locally controllable by a manager. Examples include both the fertilization effects (Mayeux et al. 1994) and potential climate changes (Graedel and Crutzen 1989) from our alteration of atmospheric chemistry, such as increasing CO<sub>2</sub> concentration. Increases in CO that have already occurred are affecting individual species differently (Johnson et al. 1993, Polley et al. 1993). These differential effects are changing competitive interactions of every community in the biosphere. Other examples of indirect impacts include the increasing UV radiation levels from the thinning of the ozone layer, many types of air pollution, and the regional to continental introductions of exotic plant species, pests, and diseases. Direct impacts are all the local to regional site specific land use activities that are more or less directly controllable by the manager. Management options for even the direct impacts are

constrained somewhat by what is possible within the influence and limitations of the indirect impacts.

The ongoing trajectories of community change from the past are now being modified, and in some instances rates of change accelerated, by the impacts from human activities. These changes are moving communities in entirely new directions. Despite the accelerated rate of these changes, and the new directions in community trajectories represented, they are still generally going unnoticed. This lack of recognition is occurring because the structure and function of communities and ecosystems are being affected on spatial scales that encompass entire landscapes and are occurring on time scales where they are often not noticeable.

Present climate and associated communities are unique for the most part and did not exist in the past (Tausch et al. 1993a). There was little chance before our impacts on the biosphere that a particular sequence of environmental changes will exactly repeat itself into the future to result in the same kind of communities now present. With our current and ever increasing impacts both the sequence of environmental changes and the communities that result will be in some minor way or major way, depending on location and community, different than anything that has occurred in the past.

Since ecosystems are transient they should not be viewed as a particular state, but as a range of states over the landscape that represent the essential parts of their cycles of change. All we can really manage are the multiple trajectories of change occurring over the

landscape. To manage these trajectories of change we need to know what the trajectories are. We need to know where communities have been, what have been their trajectories of change from then to now, and what changes are likely to occur into the future. Management decisions will involve either maintaining or changing these trajectories.

In both the past and the present we have lacked a focus toward understanding the trajectories of community and ecosystem change. This appears to have resulted primarily from a general lack of understanding of both the magnitude of past changes resulting from human impacts and the fact that these changes have been ongoing for centuries. In effect, the global change that is projected for the future is already here. There will be surprises in our future attempts to manage ecosystems. They will all affect ecosystem sustainability and management options. We have limited ability to manage so as to prevent these surprises. Thus, we need to try to manage ecosystems so they retain the resilience necessary to cope with what ever changes the future may bring. This will require management paradigms that do not foreclose on future options.

Our perceptions of the importance of ecosystems and the complexity of their management parallel the growth both in our population size and in the complexity of our social needs and economics. When population levels were low and societies simple, impacts were limited and most systems could absorb the impacts relatively well. The level of complexity in expertise and

expense required to deal with the resulting impacts was also low. As societies have become more complex, as population levels have risen, and as our activities have intensified the level and extent of human impacts has increased. As the impacts have become more pervasive, more of the structures and functions of ecosystems have been affected. The scales of time and space involved have also increased. As a result, the affected systems became less able to absorb the increased level of impacts as more of their structures and functions were affected. The more an ecosystem is affected, the more complex are the associated biotic responses. As the responses by ecosystems become more complex, the expertise and expense necessary to successfully correct or even cope with those responses becomes greater. Our impacts are now so numerous and pervasive, particularly in the indirect impacts, that no ecosystems are unaffected and all levels of their structure and function are influenced to at least some degree. As a result, the level of expertise and expense now required to fully deal with, or to at best, moderate the negative results of our current impacts is very high. Potential expenses are clearly so high that it is probably not economically possible to mitigate all of our current impacts. There will be, as a result, many tough choices and tradeoffs ahead.

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# An Analysis of Drought in the Northern Great Plains: Summary of Progress<sup>1</sup>

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**Abstract.**—Progress is summarized on development of tree-ring chronologies (Sieg *et al.*, In press), preliminary analyses on the relationship between annual tree-ring widths and both precipitation and soil moisture (Ni 1993), and efforts to identify climatic regions (Bunkers 1993) and drought patterns (Bunkers *et al.* 1993) from climatic records.

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Global circulation models (GCMs) predict that summer soil moisture in the Northern Great Plains will decline under CO<sub>2</sub>-induced warming (Manabe and Wetherald 1986). Tree-ring data can be used to place such predicted declines in the context of natural climate variability. Tree-ring studies aimed at documenting the drought history of the Great Plains have been hindered by a lack of tree-ring chronologies because of the scarcity of trees in the central parts of the Plains (Stockton and Meko 1983; Meko 1992). The purpose of this research is to increase the understanding of the magnitude, recurrence interval and periodicity of drought in the Northern Great Plains both from dendro-chronological reconstructions and from analyses of available climate data.

The objectives are to: (1) develop a network of climatically sensitive tree-ring chronologies to fill a void in the Northern Great Plains; (2) isolate climate variables most highly correlated with tree-growth; (3) reconstruct the drought history for the past 100 to 300 years; (4) identify regions

which are climatically similar with respect to drought; (5) isolate patterns of drought persistence or recurrence; and (6) determine if drought recurrence is related to southern oscillation events.

This paper summarizes progress on development of tree-ring chronologies in the Northern Great Plains (Sieg *et al.*, In press), preliminary analyses on the relationship between annual tree-ring widths and both precipitation and soil moisture (Ni 1993), and efforts to identify climatic regions (Bunkers 1993) and drought patterns (Bunkers *et al.* 1993) in this region from climatic records.

## Collection and Development of Tree-ring Chronologies

We collected tree-ring samples from 53 separate sites in the Dakotas and Iowa in 1991 and 1992, with the goal of developing a widely-distributed network of long, climatically sensitive chronologies. The properties of 23 chronologies, in terms of chronology length, sample depth (number of trees), consistency of tree-

ring patterns among trees, and correlation between tree-ring series and precipitation have been summarized (Sieg et al., In press). Tree species in the collection include: bur oak (*Quercus macrocarpa*), ponderosa pine (*Pinus ponderosa*), and Rocky Mountain juniper (*Juniperus scopulorum*).

Earliest dates of specimens are 1281 A.D. for pine, 1597 for juniper and 1676 A.D. for oak. The mean between-tree correlation of ring-width indices at the various sites ranges from 0.33 to 0.57. A total of 13 of 23 sites reach an expressed population signal (the chronology signal expressed as a fraction of the total theoretical population) of 0.85. Correlation analysis indicates that tree-ring widths on most sites are more highly correlated with annual precipitation (September - August) than with spring and early summer precipitation (April - July). Sites with relatively high precipitation signals were found for each species, but a decrease in sample size in earlier years generally limits the period of reliable climate inference from the widely distributed oak chronologies to the mid-1800s. The period of reliable inference for the western Dakotas (from pine and juniper) extends to the early 1600s, and could probably be extended to earlier centuries with additional collections.

### **Isolation of Climate Variables Associated with Tree Growth**

Tree-ring data from nine bur oak and six ponderosa pine chronologies were used to investigate the relationship between annual ring width and soil mois-

ture in the Black Hills area of western South Dakota and eastern Wyoming. Soil moisture values were developed from a water balance model, using climate data from weather stations in the area.

The analysis of tree-ring chronologies and climate and water-balance variables shows a strong relationship between annual ring growth and both precipitation and soil moisture (Ni 1993). The consistency of the relationship between chronologies and climate variables over time was explored using correlations with variable year periods. Correlations for a 23-year period were uniformly high - on the order of 0.5 to 0.7 - throughout the instrument period, indicating a stable relationship.

### **Identification of Climate Regions Based on Regional Climate Data**

Monthly total precipitation and average temperature data were collected for 174 stations in the Dakotas and the area bounded by 1° in both latitude and longitude surrounding the Dakotas. Records extended from the late 19th century to 1990. These data were analyzed to identify: (a) homogeneous climate regions and (b) patterns associated with the warm (ENSO) and cold (LNSO) phases of the Southern Oscillation (SO).

A combination of principal component and cluster analyses was used to identify 21 climate regions, of which three encompassed the Black Hills (Bunkers 1993). This area is currently defined as one division by the

National Climatic Data Center. Delineation of climate divisions based on climatic gradients results in more useful divisions than those based on political and/or geographic boundaries.

Five seasons with significant changes in mean temperature or precipitation during either ENSO or LNSO were identified. For ENSO a significant signal was evident during April to October, where precipitation during 20 of 23 ENSO events was above the median value. In contrast, a strong signal for decreased LNSO precipitation was noted where May to August precipitation during 13 of the 17 LNSO events was below the median value. In general, temperature responses were strongest in the northern part of the region; precipitation responses were strongest in the southern part. The relationship of climate anomalies to SO events combined with the ability to predict these phenomena several months in advance will provide enhanced opportunities for better informed management decisions.

### **Growing Season Drought in South Dakota from Precipitation Records**

Regional climate records are generally less than 100 years in length, and therefore are insufficient to identify periodic fluctuations in climate with confidence. However, these data may be examined for trends in annual precipitation and temperature.

The 1930s were, by far, the worst period of drought in the century, and had the largest decrease of growing season precipitation in western South

Dakota (Bunkers et al. 1993). Spatial gradients in precipitation and temperature were observed across the state. For example, an early-to-mid 1980s wet period was evident over southeastern South Dakota, but average precipitation fell over the western third of the state. Finally, the mean growing season temperature exhibited more variability at the 10-year time-scale; conversely, the mean growing season precipitation fluctuated more at the 20-year time scale.

### Summary

An understanding of both recent and historic drought recurrence is necessary to place predictions of decreased soil moisture from CO<sub>2</sub>-induced warming in the context of natural climate variability. These studies will assist in planning for future droughts in the Northern Great Plains and will result in more informed land management decisions.

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# Engelmann Spruce Tree-Ring Chronologies from Fraser Experimental Forest, Colorado: Potential for a Long-Term Temperature Reconstruction in the Central Rocky Mountains<sup>1</sup>

Peter M. Brown and Wayne D. Shepperd<sup>2</sup>

## Introduction

A major question arises when attempting to assess potential human-induced climate change in the late twentieth century: what has been the natural variability of climate regimes, especially on decadal to century scales? To answer this question, paleoclimatic data are crucial to provide longer-term records of climate variability against which to compare present and future climate fluctuations. Here we describe the development and analysis of two Engelmann spruce (*Picea engelmannii* (Parry) Engelm.) tree-ring width chronologies from near-treeline sites in the central Rocky Mountains. These chronologies are the longest such chronologies yet developed from this area and can be associated with late spring temperatures for this region. These chronologies offer the possibility of reconstructing seasonal tem-

perature variation extending back to the mid to late 1200s over a large portion of the central Rocky Mountains.

## Chronology Development

The two sites where ring width chronologies have been established are just below treeline on opposite sides of the main St. Louis Creek drainage at Fraser Experimental Forest (fig. 1). The Fool Creek chronology (FCC) site is located at the head of Fool Creek drainage at an elevation of 3505 m, about 30 m to 40 m below present day treeline. St. Louis Lake (SLL) site is near the southern headwaters of St. Louis Creek at an elevation of 3530 m, about 10 m to 20 m below treeline. Both sites are

**Abstract**—Tree-ring width chronologies from Engelmann spruce at two treeline sites in the central Rocky Mountains contain similar high and low frequency patterns in ring width, indicative of regional climate control on tree growth. Comparisons of annual ring widths with instrumental climate data show relationships with late spring temperature fluctuations on annual to century time scales. Ring width patterns in the earliest dated trees at one of the sites also infers upward migration in treeline at the site around A.D. 1250. No unusual growth increases were seen in recent years, suggesting that these trees have not recorded warmer conditions possibly associated with global climate change.

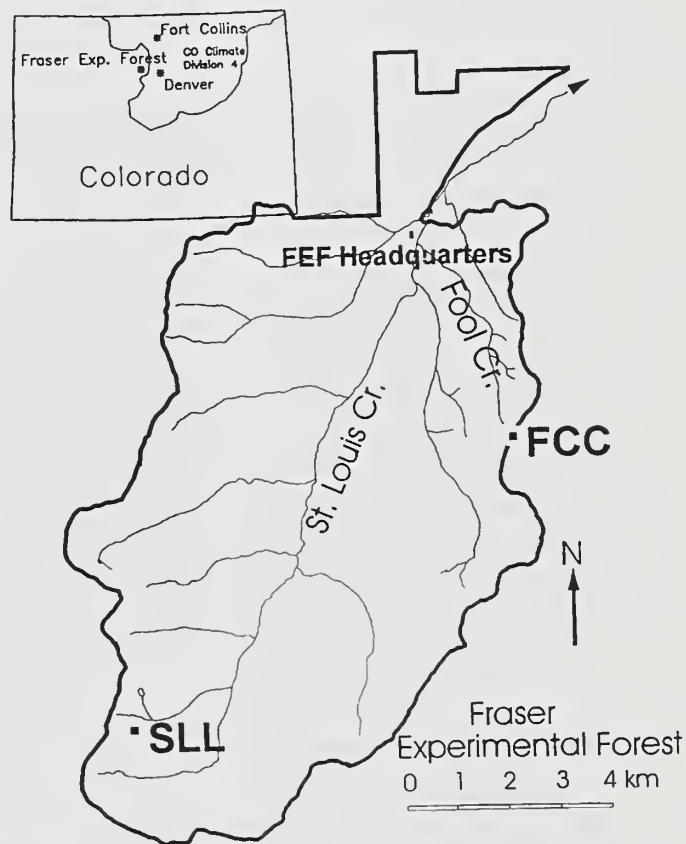


Figure 1.—Locations of Fool Creek (FCC) and St. Louis Lake (SLL) sites at Fraser Experimental Forest. Colorado Climate Division 4, the Platte River drainage, is outlined in the insert map of Colorado.

composed of open stands of pure Engelmann spruce with sparse understory vegetation, primarily *Vaccinium* sp. The distance between the sites is approximately 10 km.

At each site, increment cores were extracted from living trees,

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downed logs, and standing snags. At FCC, several remnant (dead) trees were sectioned with chain-saws or crosscut saws. All tree rings were crossdated prior to measuring of ring widths. After measuring, individual ring width series at each site were detrended with cubic smoothing splines with a 50% frequency response of 250 years (Cook and Peters 1981). Detrending involved dividing each yearly ring width by the corresponding spline value to remove age related growth trends and to stabilize mean and variance (Fritts 1976, Cook and Kairiukstis 1990). Detrending with smoothing splines of 250-year frequency response retained all variance in the ring widths associated with wavelengths of approximately 110 years or less. After detrending, ring width index series were combined into a chronology by use of a bi-weight robust mean designed to lessen the influence of outlier values (Cook 1985).

These are the longest Engelmann spruce chronologies yet developed for this area of the Rocky Mountains. FCC extends from A.D. 1222

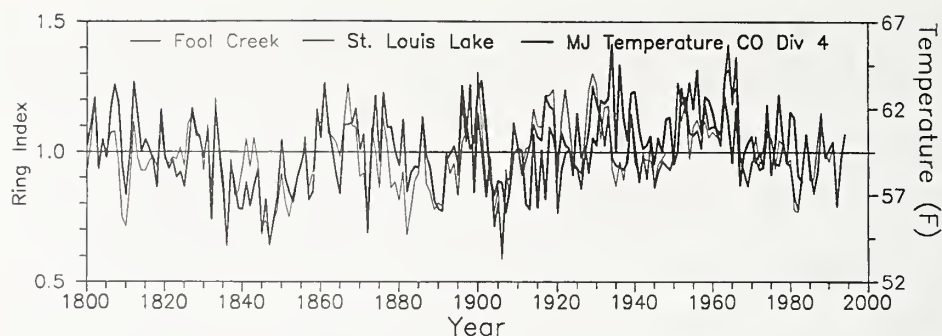


Figure 3.—Annual ring width indices for Fool Creek and St. Louis Lake chronologies from 1800 to present compared to averaged May and June temperatures for Colorado Climate Division 4 from 1895 to 1988.

to 1992 (771 years) and SLL from A.D. 1500 to 1994 (495 years), with good sample replication at both sites for most of those time periods (fig. 2). The simple correlation between the two chronologies is 0.74, suggesting that trees at the two sites were responding similarly to year to year climate variability (fig. 3). Correspondence of low-frequency ring width patterns between the two sites (fig. 2) also suggests that they were responding similarly to climate on decadal to century scales.

The FCC chronology contains the oldest known Engelmann spruce tree, with rings extending from 1152 to 1993 (Brown et al.

1995). This tree (FCC 19) and the only other at the site that grew prior to 1250 (FCC 78) both show very suppressed rings and reaction wood in the earliest portion of their ring series (fig. 2). These ring width patterns resemble those seen in krumholtz trees growing at treeline today. Both FCC 19 and 78 exhibited dramatic growth releases at around 1250 (fig. 2), which is also when several pith or near pith dates were recorded on other trees at the site (Brown et al. 1995). The period after 1250 also had the highest growth rates over the past 771 years (fig. 2). Our interpretation of these patterns in ring widths is that around 1250, trees FCC 19 and 78 were released from a krumholtz growth form at the same time as other trees were establishing at the site. This interpretation suggests that a major uphill movement of treeline, possibly as much as 30 m to where treeline is today, occurred in this area at that time.

### Relationships between Climate and Tree Growth

The ring width chronologies have been compared to climate

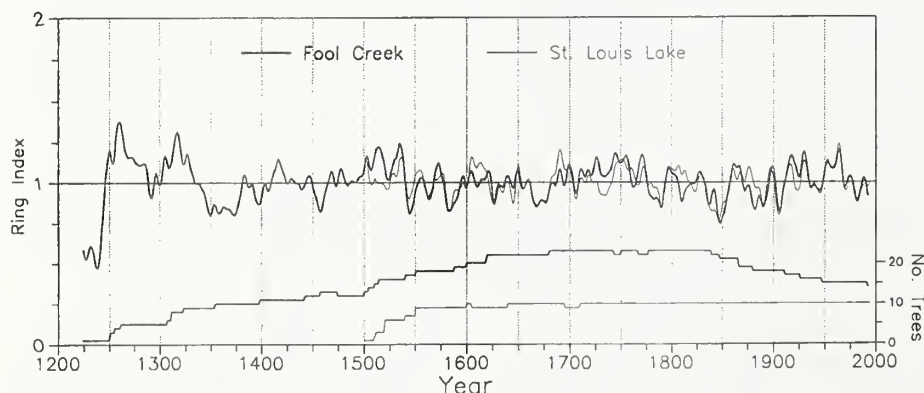


Figure 2.—Low-pass filters fit through Fool Creek and St. Louis Lake ring width chronologies and sample depth (number of trees per year) for each chronology. Low-pass filter was designed to emphasize decadal scale variability in the time series.

data from Fraser Experimental Forest Headquarters and regional averages for Colorado Climate Divisions. Climate data used were monthly and seasonalized values of temperature and precipitation for the current and previous years of growth. For comparisons with ring width data, both correlation coefficients and response functions (Fritts 1976) were used. Response functions are eigenvalues of monthly data designed to remove autocorrelation before computation of correlations with annual ring width indices.

Both response functions and correlations between climate data and ring width indices showed almost no response of tree growth to precipitation variables. This is not surprising in these high subalpine locations where soil moistures remain high throughout the short growing season. Villalba et al. (1994) also found no significant relationships between Engelmann spruce ring widths and precipitation variables at a mesic subalpine site they examined.

However, we did find strong relationships between ring indices and late spring temperatures using both the local Headquarters

data and a regionally averaged dataset from Colorado Climate Division 4, the Platte River Basin (fig. 1). A best subsets regression approach with Headquarters monthly temperatures yielded a linear regression model that accounted for almost 38% ( $R^2$  adjusted for loss of degrees of freedom) of the variance in the tree-ring chronologies using as the predictor averaged April, May, and June temperatures (fig. 4). These are the months during which temperatures can most affect tree growth in these high treeline environments. Villalba et al. (1994) found a similar strong relation between tree growth and late spring/early summer temperature at their high, mesic spruce site.

In addition to the local relationship with late spring temperature, we found longer-term relationships between regional (Division 4) May-June averaged temperatures and low-frequency patterns in the ring width data (fig. 3). While there are graphical similarities between the tree ring and climate data, yearly regressions were only weakly significant at 0.26 adjusted  $R^2$ . However, Division 4

annual data are averages from climate stations in the Platte River drainage, which is east of the Continental Divide from Fraser Experimental Forest (fig. 1). A more localized regional average from stations on the Front Range and within the Fraser area may more closely model the ring width data and this will be explored further. The relationships found so far between climate data and tree growth suggest that while year to year variability in growth is best modeled by local climate records, the chronologies also contain a record of regional late spring temperature fluctuations. These findings should offer the possibility to reconstruct variability in temperature on decadal to century time scales over the last 700+ years for this region of the central Rocky Mountains.

## Conclusions

Growth and establishment patterns in the very earliest portion of the Fool Creek chronology suggest that treeline may have moved uphill at this site around A.D.1250. Strong relationships between tree growth and late spring averaged temperatures in both the Fool Creek and St. Louis Lake chronologies also would suggest that we have the potential to reconstruct seasonal climate since the mid to late 1200s for this area of central Colorado. No unusual increases in tree growth are evident in the last years of this century, suggesting that these trees are not recording any late-spring warming trends that may be related to human-induced global climate change.

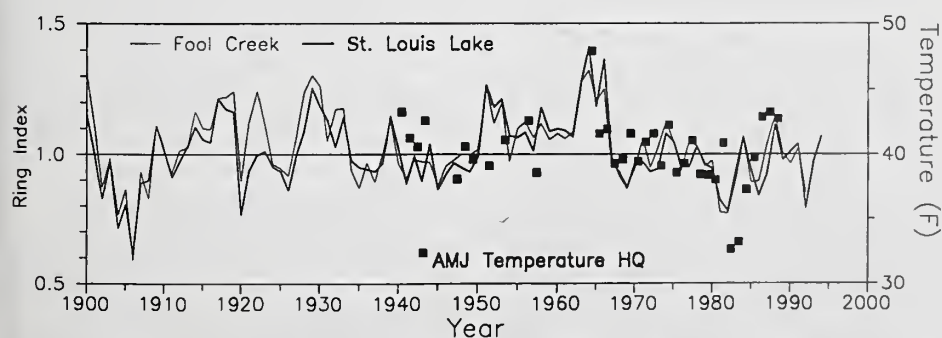


Figure 4.—Annual ring width indices for Fool Creek and St. Louis Lake chronologies from 1900 to present compared to averaged April, May, and June temperatures from Fraser Experimental Forest Headquarters. Temperature data are spotty from 1940 to 1963 and continuous from 1964 to 1988.

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# Historic Interrelationships of Humans and the Ecosystems of the Middle Rio Grande Basin<sup>1</sup>

Dan Scurlock<sup>2</sup>

The overall and specific spatial-temporal impacts of historic human activities on the land and water of the Middle Rio Grande Basin (MRGB) have only recently been a focus of researchers. Interrelationships of these and the effects of periodic severe cold periods, early or late frosts, droughts, insect infestations, and other "natural disasters" such as epidemic diseases, earthquakes, fires, and floods have been minimally explored but not systematically studied. Furthermore, the equally complex history of plant and animal introductions and extinctions by humans, although generally understood, still needs additional research as to temporal-spatial occurrence and impact on other biotic components. Finally, the role of world view exhibited by various groups as related to environmental impact, change, and future resource management needs must be considered.

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**Abstract.**—An ongoing study of the environmental history of the Middle Rio Grande Basin, New Mexico, is revealing major impacts on and changes to ecosystems over the past 455 years. Various land uses, such as grazing, irrigation farming, logging, and constructing flood control features, combined with climatic fluctuations have adversely produced changes in stream flow-morphology, ground water levels, topsoils, biotic communities, and individual species. Indigenous human populations have been adversely impacted by these modifications as well. Continued land-water use-impacts from a rapidly increasing regional population portend continuing changes and major challenges for natural and human resource management agencies and organizations.

Droughts, floods, severe cold, and deep snow influenced or directly impacted many activities, notably travel, agriculture, livestock raising, warfare, hunting, and gathering during the historic period (A.D. 1540-present). Extended dry periods and otherwise sporadic short-term and long-term precipitation were significant limiting factors and were interrelated with such environmental conditions as soil erosion, decrease in wildlife populations, change in plant community species density and composition, and fluctuations in surface and ground water hydrology.

The various effects of extended cold winters or shorter periods of below normal temperatures associated with high winds and snow (blizzards) and above normal snowfalls were significant impacts, as well. Events of these kinds commonly occurred during the "Little Ice Age," which gripped New Mexico from about the mid-fifteenth to mid-nineteenth centuries. Adverse effects of this cold period included human fatalities, crop and livestock losses, and general unrest and suffering. The warming period and relatively frequent

droughts which followed, especially from the 1860s to the 1950s, adversely impacted ranching and farming economics as well, and human population shifts and trends.

Detailed climatic records before 1850 are limited, although tree-ring data provides some understanding of climate fluctuations and long-term patterns in the study region. Comprehensive systematic studies of scientifically recorded climatic records which date from the late 1840s-early 1900s in the MRGB are underway. Associated data, such as stream flow records of the past 120 years or so, are now being synthesized and analyzed, as are comparative climatological data from tree-ring studies.

Probably the single most significant climatic factor affecting human populations negatively during the historic period was drought. Occurring region-wide or locally, droughts damaged or destroyed crops and rangelands, decimated wildlife populations, and depleted water supplies. These impacts sometimes resulted in widespread suffering, and even loss of human life and the shifting of human populations.

Historical documentation from the mid-seventeenth century to the late nineteenth century generally support more recent detailed weather records which suggest the occurrence of a major drought in the region every 20 to 25 years. These periodic droughts, increasing use of surface and ground waters, and intensive grazing have generally resulted in dramatic changes in the flora.

Wildfires caused by lightning were a common phenomenon during the period of greatest lightning-strike frequency which was and is July to September. The highest occurrence of these natural fires appears to be correlated with *la niña*, or drought years. Native Americans used fire as one method of clearing the bosque for cultivation. Only in this century have naturally caused woodland or range fires on the adjacent grasslands been suppressed in the region. In the late prehistoric and historic periods Native Americans burned grasslands and woodlands to drive game animals to a location where they might be more easily killed, as well as to stimulate new plant growth.

Range fires usually killed small woody species whereas grass regeneration was stimulated. Reduction of dense stands of dry grasses by overgrazing also reduced available fuel for range fires and decreased competition from grasses allowing propagation and growth of woody plants. Woody shrubs and small tree species such as juniper, fourwing saltbush, and pinyon have encroached on semi-desert grasslands adjacent to the valley as a result of fire suppression.

The impact of introduced European diseases such as smallpox on Native Americans has been relatively well-documented in New Mexico; more Indians died of epidemics in the colonial period than any other single cause. These serious maladies contributed significantly to unrest in the province, some of which resulted in several 1600s Pueblo revolts and increased raiding by nomadic Indian groups. The latter phenomenon was also interrelated with severe, extended drought conditions in the 1640s, 1660s, and 1770s-early 1780s and produced the most catastrophic periods of conflict and war in the colonial period.

Various groups in the Middle Rio Grande Basin have greatly affected the processes and evolution of plant and animal communities during the past four and a half centuries, i.e. A.D. 1540 to the present. The human generated impacts and changes, through activities such as farming, ranching, hunting, ranching, mining, logging, stream impoundment, and recreation, have altered the structure, function, and dynamics of ecosystems over the past 455 years. Some of these activities, which have reduced vegetative cover, combined with periodic droughts and fires, have resulted in high rates of surface run-off because of precipitation and associated erosion. Silt from this event has, generally, increased through time, and the resulting impacts on riparian plant and animal communities have been, in cases such as the Middle Rio Grande Valley and major tributaries such as the Rio Puerco, severe. Other impacts such as the introduction of exotic species of plants

and animals, various toxins, the diversion of water for irrigation and the construction of water control dams have also brought dramatic changes to riparian ecosystems. Additional impacts on riparian communities, as well as on upland ecosystems-grasslands, pinyon-juniper and ponderosa woodlands, and montane mixed conifer forests—are noted in the following overview.

In the late sixteenth century-early seventeenth century, the Spanish brought with them new technologies and a number of new domesticated plants and animals, which had a decisive impact on Pueblo, Navajo, and Apache diet and landscape. Introduced livestock included sheep, goats, horses, mules, burros, oxen, cattle, hogs, and chickens. Introduction of metal tools such as the axe, which made cutting green wood easier and faster, as well as iron-tipped plows and various metal weapons, had a significant adverse impact on native fauna, flora, as well as soils. New cultigens included wheat, barley, cabbage, onion, lettuce, radish, cantaloupe, watermelon, and several species of fruit trees, as well as native Mexican Indian crops such as chile, cultivated tobacco, tomato, and new varieties of corn and beans. Some introduced non-cultigens, such as alfilerillo and horehound, became established in fields and other disturbed areas.

Limited mining in the colonial period by both Spaniards and Pueblos impacted local ecosystems in a variety of ways. The best known of these locales are the turquoise and lead mines in the Cerrillos area, north of the Sandia Mountains. Pinyon, juniper, and

oak were cut for "smelting" fuel-wood, mining timbers, and structures. Some local water pollution was generated by these mining activities as well.

Around gold, silver, and copper mines in the Ortiz, Sandia, and Jemez mountains, the land was denuded of trees by wood cutters who used them to make support timbers and charcoal for the mines. The relatively sharp increase in livestock numbers, especially sheep, during this period was because of the growth in mining markets to the south in Mexico (and later California). This intensive and widespread grazing resulted in loss of vegetative cover and subsequent erosion in various locales. Grass shortages on Spanish land grants led, in part, to encroachment of Mexican flocks and herds on Pueblo crop and rangelands, additional erosion of hillsides, and the siltation of river and stream beds and irrigation facilities.

During the Mexican Period (1821-1846), some of the effects of settlement and land use on the natural environment were recorded by both government and ecclesiastical officials. Overgrazing around old settlements and nearby valley and upland rangelands, begun in the colonial period, intensified and flocks of sheep increased. Some of the choice grazing areas in the region were cienegas and other wetlands, which were heavily impacted by livestock during this period. Livestock trails turned into linear arroyos, and silt-laden run-off increased.

The arrival of relatively large numbers of Anglo-American military personnel, ranchers, and settlers, beginning in 1846, had the most significant impact on

New Mexico's environment. Although these groups did not introduce a large number of new domesticated plants and animals, their implementation of more intensive land use patterns, coupled with new technologies, increasingly contributed to the ongoing erosion of hillsides and siltation of river beds, the extermination or reduction of several animal species, and the decimation and fragmentation of plant communities. The rapid growth of the range cattle industry in New Mexico after the Civil War led to increased grazing of grasslands and contributed to flood-related events specified above. Overgrazing along streams, at other wetland sites, and at windmill tanks occurred. Anglo ranchers, unlike Native and Hispano Americans, suppressed range fires. This action, combined with overgrazing, caused native plant species such as broomweed, cholla, prickly pear cactus, sagebrush, and less desirable grasses to spread and increase on pristine grasslands. The exotic Russian thistle and several introduced grasses also proliferated. Consequently, the carrying capacity of New Mexico's rangelands was reduced significantly during this period.

Military forts, mining camps, and railroad construction made heavy use of natural resources such as trees for both building and fuel supplies, harvesting of native grasses for "hay," and local game, such as grizzly and black bears, bighorn sheep, deer, elk, pronghorn antelope, and several species of birds, for food and "sport." Major stream pollution occurred at many mining sites, killing associated fauna and flora

and poisoning water supplies. Many of these mining sites were abandoned, leaving open pits and shafts and toxic spoil deposits. Air quality was also negatively impacted by the railroad and mine smelters, and these technologies were the first serious sources of noise pollution in the territorial period.

Early sawmills in or near such settlements as Santa Fe, Taos, and Albuquerque resulted in the first extensive clear-cutting of forests. As a result, soil erosion was accelerated at these locales, and habitat loss contributed to the reduction of wildlife populations. The severity of floods increased, with associated impact on settlements, agriculture, and ranching.

Intensified irrigation farming impacted stream hydrology and increased salinization and waterlogging of soils in the Middle Rio Grande Basin in the late nineteenth and early twentieth centuries. Increased sediment loads in the river and its tributaries caused the streambed of the Rio Grande to aggrade, enhancing the effects of overbank flooding and bringing the water table near or to the surface of the floodplain. This resulted in the loss of thousands of acres of agricultural land by the early statehood period and was a factor leading to the creation of the Middle Rio Grande Conservancy District in 1926. The drainage systems, dams and reservoirs, and levees which were constructed by this agency produced a new set of environmental problems, such as a rapid drop in shallow ground waters, flooding of habitat, and diminution of native *bosques*, the impacts of which have only recently begun to be addressed.

Railroads were both influenced by and, in turn, affected the environment in several adverse ways. Topography, in particular the requirement for low grades and the need for water for steam engines every ten miles, played a significant role in the choice of route. Rail routes generally followed stream valleys, causing damage to riparian biotic communities and polluting streams. Train engines were often the cause of range or forest fires (ignited by ashes and sparks) and other environmental change. Railroad construction also impacted forests (mainly for ties and locomotive fuel) and streams (siltation from exposed soils). Animal populations were subjected to additional pressures as commercial hunters harvested meat animals to feed the railroad construction crews. Deer, pronghorn antelope, and elk were the main game species; elk populations were eradicated in some areas by 1900.

Commercial, subsistence, and "sport" hunters during the late 19th and early 20th centuries had sharply reduced or exterminated populations of native game animals such as pronghorn antelope, elk, bighorn sheep, and Rio Grande turkey. This over harvesting resulted because of the lack of regulatory game laws, more efficient firearms and ammunition, an increasing number of hunters, and a philosophy that there would always be wild animals of any kind to hunt. In response, the New Mexico Game and Fish Department was created by the territorial legislature in 1904. Both state and federal regulatory laws were subsequently passed.

During this period farmers, ranchers, and the general hunter population also killed large numbers of predators, notably the grizzly bear, gray wolf, Mexican wolf, coyote, and mountain lion. Beginning in the second decade of this century state and federal agencies joined in an effort to exterminate the grizzly and the two wolf sub-species. By the 1930s they had eradicated two of the three; a few Mexican wolves survived in extreme southwestern New Mexico until the 1950s.

At least 50% of the fish were exterminated in the middle Rio Grande drainage between the 1870s and recent years. Competition with exotics, loss of habitat, and water pollution were the primary causes of this eradication.

Exotic animal species and a number of plants were introduced and naturalized during Statehood period (1912-present) and became, or have become, ecological-economical problems. These species were either inadvertently or purposely introduced. Some of the introduced animals included the Norway rat, house mouse, burro, horse, and several species of amphibians and fish. The most troublesome introduced plants are tamarisk, tree-of-heaven, Russian olive, Russian thistle (tumbleweed), and Siberian elm.

### **Research Needs, Strategies, and Goals**

Extant and new historical and archeological data, retrieved and analyzed during this project will provide the environmental context and baselines for use in

addressing the following problems delineated by team biologists and archaeologists.

1. Need for a better understanding of the long-term responses of ecosystem components—soils, nutrients, water, flora, and mycorrhizae—to past and present perturbations caused by climate change, fire, herbivore grazing, irrigation and dry farming, logging, fuelwood harvesting, and other human activities. Secondly, these historical data will shed light on how such responses influence ecosystem dynamics, stability, and productivity of upland communities.
2. Need for a better understanding of upland biotic communities, including the historic, spatial, and temporal interrelationships with fluvial ecosystems.
3. Need for a better understanding of how humans adapted to changing environmental conditions, both "natural" and human-induced, and to determine when and how these perturbations occurred and what the consequences were. These data will be used to determine sustainability of traditional land-water activities today and more importantly, in the future.

4. Need for a better understanding of the evolution of basin ecosystems in terms of human interactions related to cultural elements—"world view," use of resources, and economics—and how these land-water use histories relate to conflicts between specific groups. Collected data for use in planning future management for sustainability of resources as related to differing group views will afford a more sound basis for such decision-making.

To assist in addressing these four major problems, the following research is in progress:

1. Reconstruction of historic climatic regime for the overall basin and specific locales.
2. Reconstruction of morphological dynamics of the Rio Grande and major tributaries related to floods and human use-management.
3. Reconstruction of water flow data and interrelationships with climatic fluctuations and human use.
4. Reconstruction of historic fire history.
5. Reconstruction of ecological-human-induced changes in ecosystem components.

6. Reconstruction of overall and site-specific grazing history and impacts.
7. Reconstruction of regional and specific-site farming history.
8. Reconstruction of changes in plant and animal communities and particular species populations over time related to human use, climatic change, and exotic species introductions.
9. Reconstruction of human responses to these changes.
10. Reconstruction of adaptations of various groups to the same sub-regional, or area, environments.
11. Examination of the similarities and/or differences in Pueblo agricultural techniques and production along streams such as the Rio Grande vs. that along Las Huertas Creek.
12. Delineation of eco-cultural areas based on spatial-temporal distributions of specific groups related to identifiable ecosystems.
13. Comparison between the exploitation strategies of different populations, e.g. Hispano and Anglo livestock raisers utilizing the same resource area, as well as the impact of that utilization, will be addressed.

14. Construction of models of ecosystems, including humans as a major factor in the dynamics and change of these systems (Santa Fe River, Rio Puerco, Las Huertas, Tijeras Arroyo, and sections of Rio Grande, such as the Bosque del Apache and Isleta Pueblo areas [including the wetlands]).

The following four spatial and temporal models of the Middle Rio Grande Valley historical ecosystem will be tested using data collected and analyzed. The resulting revised models will provide a context for better bioremediation, evaluation of sustainability of land use practices, and development of appropriate management programs.

## Model I: MRGV in 16th Century

### Historic Stream Hydrology-Morphology

- Perennial flows, relatively deeper, larger volume of water.
- Transport of relatively low sediment load.
- Braided, slightly sinuous, aggrading, shifting sand substrate.
- Overbank flooding with two peaks — April-early June (snowpack melt, highest water flow); August-September (intense precipitation on watershed).

- Shifting river channel and movement across flood plain (avulsion).
- Island and sand bar formation - destruction.

### **River-Floodplain Biological-Eco-cultural Components**

- Grass meadows, *cieneegas*, *charcos* (ponds or small lakes).
- Varied, changing age structures of cottonwood-willow stands.
- Wildlife diverse and relatively abundant.
- Life forms present—wolf, river otter, mink, whooping crane, Rio Grande turkey, shovelnose sturgeon and 11 other fish species — which were later extirpated.
- Ca. 30,000 acres of floodplain under Pueblo cultivation.
- Limited Pueblo diversion of river for irrigation.

### **Model II: MRGV in 17th-Mid 19th Centuries**

#### **Historic River Hydrology-Morphology**

- Somewhat decreased stream flows and associated diminution of volume.

- Flow widening and becoming more shallow.
- Braided, sinuous, increasing aggradation of streambed.
- Overbank flooding and avulsion more frequent and severe.
- Increased frequency of channel shifting resulting from intense floods.
- River banks and islands less stable.
- Increasing sediment load because of various land-use practices.
- Gradual rise of groundwater levels under floodplains.

### **River-Floodplain Biological-Eco-cultural Components**

- More fragmented and reduced stands of cottonwood-willow communities because of human use and intense floods.
- Increased alkalinity and waterlogging of soils.
- Increased number of grass meadows, *cieneegas*, and *charcos*.
- Less stable and decreasing populations of faunal communities.
- Increase to ca. 100,000 acres under cultivation by

Pueblos, Hispanos, and Anglos.

### **Model III: MRGV in Late 19th Century to Early 20th Century**

#### **Historic River Hydrology-Morphology**

- Continued decrease in flows, increase in sediment load, and aggradation of river.
- Flood frequency and intensity increased.
- Some scouring and incising of river channel because of floods.

### **River-Floodplain Biological Eco-Cultural Components**

- Increased soil alkalinity and waterlogging.
- Continuing rise in water table, then lowering of water table.
- Decrease of cultivated lands to ca. 40,000 acres.
- Extirpation of several large mammal and fish species.

## **Model IV: MRGV in Mid to Late 20th Century**

### **Historic Stream Hydrology-Morphology**

- Decrease in sediment load and aggradation of river.
- Flood frequency and intensity decreased dramatically because of construction of major dams.
- Continued lowering of water table.
- Channel straightened and bermed, channel shifts virtually halted, and banks stabilized.
- Floodways cleared and channel modified.
- Continued reduction of wetlands.
- Construction of several ponds.
- A small number of exotic plant species and a number of fish introduced.
- Less stable and severe decrease in some wildlife populations; other wildlife populations increased.
- A number of wildlife species extirpated.

### **River-Floodplain Biological-Eco-cultural Components**

- Highest (?) number of wetlands and associated plant communities, then severe reduction to lowest in historic period.
- Cultivated acreage increased to perhaps 125,000 acres by Euro Americans and Pueblos, then decreased to 35,000 acres because of environmental changes, then cultivated acreage increased subsequently to 58,000 acres.
- Increased alkalinity and waterlogging of valley soils.

### **Beneficiaries of Research**

In addition to potential data uses by various public eco-cultural resource management personnel and agencies, this study will be useful to a myriad of other basin communities and organizations—Pueblos, Hispanic land grant associations, Middle Rio Grande Conservancy, universities and schools, environmental groups, and private firms and individuals involved in MRGB research. Potential uses include evaluating current resource use and management, planning for bioremediation of specific locales or areas, evaluating sustainability of current land use practices, locating field trip-study area sites, and identifying critical environmental issues.

# 245 Research in Support of Strategic Planning for Climate Change<sup>1</sup>

Linda A. Joyce<sup>2</sup>

**Abstract.**—This paper summarizes the research underpinning the first assessment of climate change in the Forest Service strategic planning analysis, the 1993 RPA Assessment Update. Research involved model development as well as the implementation of a framework to link climate change scenarios, the ecosystem model assessing impacts on productivity, the forest sector model forecasting timber supply/demand effects, and a carbon accounting model assessing the impact on carbon storage.

## Introduction

Strategic planning at the national level in the Forest Service was institutionalized with the passage of the Forest and Rangeland Renewable Resource Planning Act of 1974 (RPA), P.L. 93-378, 88 Stat. 475 as amended. This Act directed the Secretary of Agriculture to prepare an Assessment decadelately that would include "an analysis of present and anticipated uses, demand for, and supply of the renewable resources of forest, range, and other associated lands with consideration of the international resource situation, and an emphasis of pertinent supply, demand and price relationship trends" (Sec. 3.(a)). Past assessments have focused on the demand and supply of timber, wildlife, range forage, water, minerals, and recreation. The 1990 Farm Bill added the additional stipulation that climate change impacts on productivity and species shifts be included as a

part of the RPA Assessment analyses. Prior to this point in time, these strategic planning analyses had not considered the potential impacts of climate change on the future uses, demand for, and supply of renewable resources (Joyce et al. 1990, Fosberg et al. 1992).

The difficulty of assessing the national effects of climate change is that experimentation is not possible. Forest Service strategic planning analyses have traditionally relied on models and the timber analyses have been the most quantitative. Information on the impacts of climate change on the complete suite of plant and animal species found on forest and rangelands was and still is not available either in field experiments or models (Joyce et al. 1990). In contrast, ecosystem models such as the Osnabruck model developed by scientists at the Osnabruck University in Germany, the Terrestrial Ecosystem Model (TEM) developed at The Ecosystem Center in Woods Hole, MA and ecosystem models at Oak Ridge had progressed to the point where regional and national models were available to experiment with climate change impacts on ecosystem productivity. Thus, the research initiated to

probe the potential impacts of climate change focused on forest productivity and the economics of the forest sector using regional and national models (Joyce 1992, Joyce and Haynes 1992).

## Research Planning for the Climate Change Assessment

In 1988, a series of studies were initiated to: (1) examine the interactions between carbon and nitrogen dynamics in estimating net primary productivity for potential vegetation in North America, (2) compare the predictions of a process-based model (TEM) and a regression-based model (OBM), (3) examine the modeling assumptions involved in processes related to soil carbon accumulation at different soil depths, and (4) develop and implement a framework to link general circulation model output, the ecological model, the timber policy model, and a carbon accounting model at the national scale. These studies are now complete (Joyce in process). We have started a study examining the relationships of climate change, productivity and international trade at the global scale (Perez et al. in process).

<sup>1</sup>Paper presented at the Interior West Global Change Workshop, April 25-27, 1995, Fort Collins, CO.

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## Interactions between Carbon and Nitrogen Dynamics in Estimating Net Primary Productivity

The Terrestrial Ecosystem Model (TEM), a process-based model, was used to investigate how interactions between carbon (C) and nitrogen (N) dynamics affect estimations of net primary productivity (NPP) for potential vegetation in North America (McGuire et al. 1992). In this study, the model was modified from its previous descriptions (Raich et al. 1991) so that photosynthesis would monotonically decrease as nitrogen stress increased. In this way, carbon uptake would respond to gains or losses in site fertility. Temperature effects on gross primary productivity and on plant maintenance respiration were also modified.

Data from intensively studied field locations was used to estimate vegetation-specific parameters for each of the 17 ecosystems (McGuire et al. 1992). To extrapolate the model to the continental scale, TEM used spatially referenced data on climate, soils, and vegetation to make monthly estimates of important carbon and nitrogen fluxes and pool sizes. Maps of potential, undisturbed natural, vegetation were digitized to a resolution of  $0.5^\circ$  latitude  $\times$   $0.5^\circ$  longitude. All abiotic and biotic data used to drive TEM were gridded at a resolution of  $0.5^\circ$  latitude  $\times$   $0.5^\circ$  longitude (Raich et al. 1991).

For North America, TEM estimates the annual NPP to be  $7.032 \times 10^{15}$  gC yr<sup>-1</sup> (McGuire et al. 1992). Estimates for forest NPP ranged from  $230$  gC m<sup>-2</sup> yr<sup>-1</sup> for boreal forests to  $1113$  gC m<sup>-2</sup> yr<sup>-1</sup> for tropical evergreen forests. At the

continental scale, TEM estimated a 32.5% increase in NPP if N were not limiting. This nitrogen limitation is weakest in tropical forests and increases in temperate and boreal forests. Along naturally occurring gradients of temperature and moisture in northern and temperate regions of the continent, both NPP and net nitrogen mineralization increase. The degree to which N limits productivity varies within ecosystem as a result of interactions between the N and C coupling and factors such as temperature. The linkage between C and N dynamics improved the spatial resolution in estimating NPP across the continent (McGuire et al. 1992).

A factorial experiment evaluated the interactions between C and N dynamics in the response of NPP to an elevated temperature of  $2^\circ\text{C}$ . In TEM carbon cycling can be uncoupled from the nitrogen cycle by setting the feedbacks of nitrogen availability to 1. Thus, the experiment was a  $2 \times 2$  factorial of nitrogen coupling (uncoupled, coupled) and temperature ( $+0^\circ\text{C}$ ,  $+2^\circ\text{C}$ ). To minimize ecosystem differences, we focused on the temperate mixed forest of North America. When only carbon cycling is considered, NPP decreases because of higher plant respiration under a  $2^\circ\text{C}$  increase. When both C and N cycles are considered, NPP increases because the warming increased N availability and this offset higher costs of plant respiration. These diametrical differences in NPP responses to climate change suggested that process-based models need to consider linkages between the C and N cycles (McGuire et al. 1992; see also McGuire et al., In press [a]).

## Comparison of TEM Model and OBM Model

While several ecological models existed at the time this research was initiated, the similarities or differences of the predicted impacts of the ecological models had not been compared. Regression- and process-based approaches for predicting biogeochemical responses of ecosystems to global change were compared in McGuire et al. (1993). A regression-based model, the Osnabruck Model (OBM), and a process-based model, the Terrestrial Ecosystem Model (TEM), were applied to the historical range of temperate forests in North America in a factorial experiment with three levels of temperature ( $+0^\circ\text{C}$ ,  $+2^\circ\text{C}$ , and  $+5^\circ\text{C}$ ) and two levels of  $\text{CO}_2$  (350 ppmv and 700 ppmv). The temperate forested ecosystems included: boreal forest, temperate coniferous forest, temperate deciduous forest, temperate mixed forest, temperate broadleaved evergreen forest, tropical deciduous forest, tropical evergreen forest.

The regression-based model, OBM, used spatially referenced information on soils, climate and land-use to estimate carbon fluxes and pool sizes. For this study, we focused only on the NPP calculations in OBM to compare with TEM estimates and did not include the land use portion of OBM. The NPP calculations in OBM were a function of annual temperature, precipitation, soil fertility and carbon dioxide fertilization.

For contemporary climate ( $+0^\circ\text{C}$ , 350 ppmv), the two models estimated similar NPP for tem-

perate forest in North America (McGuire et al. 1993). Regionally, the NPP estimates from the two models varied. While model estimates of NPP were within 20% of each other for deciduous and mixed forest types in the Ohio Valley, the estimates of OBM were lower than those of TEM both north and south of this area. In the mountainous regions of western North America, OBM estimates for conifer forests were more variable than the TEM estimates. For temperate conifer forest in southwestern Canada, the estimates of OBM tended to be lower than those of TEM.

Although the contemporary climate responses were similar at the continental scale, the two model responses to altered climates differed at both the continental scale and at the regional scale. Model responses to elevated temperature agreed most in northern areas of moist temperate forest, but disagreed in southern areas and in regions of dry temperate forest. For elevated  $\text{CO}_2$ , the responses differed qualitatively in all regions between the models. With no change in temperature and an elevated carbon dioxide level of 700 ppmv  $\text{CO}_2$ , OBM predicted median increases in NPP of 12.5% whereas TEM predicted median increases of only 2.5%. For increases in both carbon dioxide and temperature, the models differed qualitatively in their response. In OBM, increases in NPP to elevated carbon dioxide occurred only in those grid cells that were temperature-limited under contemporary climate. In TEM, NPP responses were a positive progressive increase under elevated temperature and carbon dioxide (McGuire et al. 1993).

These NPP differences under altered climates occurred because of differences in how environmental factors and elemental availability limited NPP in these models. In OBM, NPP was a function of the most limiting factor: precipitation or temperature. TEM included known feedbacks between temperature and ecosystem processes that affect N availability, photosynthesis, respiration, and soil moisture. Thus, in TEM, an increase in temperature can alter the decomposition of soil organic matter, releasing inorganic N into the soil and enhancing N availability, or may reduce soil moisture thereby reducing N availability and NPP.

Regression-based models have contributed greatly to our understanding of the global carbon cycle by organizing many fragmented studies and constructing initial hypotheses about how NPP and climate are related. However, regression-based models may not be adequate to examine ecosystem behavior under climatic conditions not now experienced by ecosystems. For example, a mean annual increase of  $+5^\circ\text{C}$  for southeastern United States may create seasonal temperatures similar to the current temperatures in the tropics, but the seasonal intercepted solar radiation may not be similar to the current seasonal distribution in the tropics. Thus, it may not be feasible to extrapolate the current combinations of environmental variables and NPP responses to the future altered climates. Further, the process-based approach allows experimentation of important feedbacks and constraints on NPP responses. The results of this study suggest that the process-

based approach is able to progress beyond the limitations of the regression-based approach for predicting biogeochemical response to global change.

## Soil Carbon Studies

In this study, TEM development focused on processes influencing reactive soil organic carbon across climatic gradients. We evaluated the sensitivity of soil organic carbon to a  $1^\circ\text{C}$  warming in an empirical and a process-based analysis (McGuire et al. in press). Inclusion of mean annual volumetric soil moisture in the empirical model explained an additional 19.6% of the variance of soil organic carbon, suggesting that soil moisture should be included in carbon models. Global and regional estimates of soil organic carbon losses differed in the empirical model but were similar in the process-based modeling approaches.

## The Impact of Climate Change on Forest Sector and Carbon Storage

The consequences of elevated carbon dioxide and climate change on forested ecosystems and the feedbacks on harvest patterns and vegetation change from the forest sector have not been addressed together. A framework was implemented to link climate change scenarios, an ecosystem model, a forest sector model, and a carbon accounting model (Joyce et al., in press, Joyce in process). Contemporary climate data and four climate

change scenarios were used as input for the Terrestrial Ecosystem Model (TEM) to estimate net primary productivity (NPP) for forests in the United States. Input and output data for TEM was gridded at the 0.5° latitude X 0.5° longitude scale. We were interested in the forested ecosystems only: boreal forest, temperate coniferous forest, temperate deciduous forest, temperate mixed forest, temperate broadleaved evergreen forest, tropical deciduous forest, tropical evergreen forest.

Differences between the NPP responses from the contemporary climate and each of four altered climates were summarized in an average (mean) response for each timber management type within the timber supply/demand regions and a maximum and a minimum response to climate change. These changes in productivity were used to modify timber growth within the Aggregate Timberland Assessment Model (ATLAS), which is a part of the forest sector model (TAMM-ATLAS) used by the Forest Service to examine timber policy questions. Lacking specific information about the transient climate and the corresponding ecological response, the adjustment to projected timber growth was a linear function of the total change in NPP from climate over the 1990 to 2065 period.

While the contemporary climate offered an ecological baseline in which climate was assumed not to change from historical patterns, economic considerations required a socio-economic baseline for the 50 year projection period. For the economic baseline, the projected future from the 1993

Forest Service Assessment Update was used. Assumptions included basic determinants of timber demands such as growth in population, economic activity and income, technological and institutional changes, energy costs, capital availability, and public and private investments in forest management, utilization, and research (USDA Forest Service 1989).

Changes in timber inventories were then translated into changes in the amount of carbon stored on private timberlands using a national carbon model (FORCARB). FORCARB accounts for carbon in biomass, soil, and the litter layer including coarse woody debris.

The largest changes in ecosystem productivity were not followed by similarly large changes in the economic sector (Joyce et al. in press, Joyce in process). Increases in NPP in the northern timber regions and slight or no responses in the southern regions were followed by larger harvest increases in the South relative to the northern regions. The cost of producing timber in the South was more competitive than the northern regions even with a greater increase in productivity in the northern regions. Harvest shifts also occurred between ownerships and between product types (softwood and hardwood). Long-term changes in carbon storage indicated that these private timberlands will be a source of carbon dioxide for all but the most optimistic climate change scenario.

## International Work

Colleagues at the Ecosystem Center, Marine Biological Lab, Woods Hole, MA, have examined the potential climate change impacts on ecosystem productivity at the global scale (Melillo et al. 1993). The results of this research have been used in a manner similar to Joyce et al. (in press) to estimate productivity shifts in forests at the global scale. The CINTRAFOR Global Trade Model is currently being used to assess potential shifts in international trade of timber within the forest sector (Perez-Garcia et al. in process).

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# 245 Simulating the Effects of Fire and Climate Change on Northern Rocky Mountain Landscapes Using the Ecological Process Model FIRE-BGC<sup>1</sup>

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and Stephen W. Running<sup>4</sup>

## INTRODUCTION

Climate is considered to be the principal determinant of vegetation distribution throughout the world (Woodard 1987). The vegetation present at a point in time is governed by the cumulative history of climate, vegetation, and disturbance processes (Ryan 1991). The distribution of the world's vegetation will change as climate changes. Moreover, the pattern and severity of disturbance will also change, especially fire (Ryan 1991).

Fire has and will continue to play a significant role in determining vegetation physiognomy, structure and species composition in the world's temperate and

boreal ecosystems (see Crutzen and Goldammer 1993, Rundel 1982). The interaction of climate, vegetation, and fire has influenced the presence and rate of most ecosystem processes in forest and rangeland settings (Heinselman 1981). Fire return intervals influence the distribution of life forms and regeneration modes present on a site (Noble and Slayter 1977). The severity of fire, which depends on the amount and type of biomass present and weather conditions at the time of the fire, exerts a strong influence on plant survivorship and regeneration. The composition and structural integrity of some ecosystems are so strongly influenced by the fire regime that they are considered to be "fire dependent" (Habeck and Mutch 1973, Wright and Bailey 1982, Turner and Romme 1994). Altered fire regimes under a future of global climate change can be expected to accelerate vegetation changes on the landscape (Ryan 1991).

Long-term ecosystem responses to fire and climate can be studied either by substituting space for time in empirical studies or through the use of ecosys-

**Abstract.**—A mechanistic successional model, FIRE-BGC (a FIRE BioGeoChemical succession model), has been developed to investigate the role of fire and climate on long-term landscape dynamics in northern Rocky Mountain coniferous forests. This FIRE-BGC application explicitly simulates fire behavior and effects on landscape characteristics. Predictions of evapotranspiration are contrasted with and without fire over 200 years of simulation for the McDonald Drainage, Glacier National Park under current climate conditions are provided as an example of the potential of FIRE-BGC.

tem process models (Shugart and West 1980, Running and Hunt 1993, Bonan and Shugart 1989). Comprehensive field studies are often costly and complex, and because fire response depends both on the fire's behavior and the site's history, results are often inconclusive. Since it is difficult to empirically determine complex ecosystem process interactions in field studies, mechanistic ecosystem models can be used to investigate these dynamic relationships (Dixon et al., 1990, Bossel and Schafer 1988, Bonan and Shugart 1989, Levine et al., 1993).

In cooperation with Glacier National Park's Global Change Research Program we developed an ecosystem simulation model called FIRE-BGC (a FIRE Bio-GeoChemical process model). The model has potential global application for addressing questions on the likely impacts of climate change on vegetation and fire regimes at the regional scale, and on vegetation and fire feedbacks to the climate system. We parameterized the model for Northern Rocky Mountain forest vegetation and implemented it in a watershed of Glacier National Park, Montana, USA.

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## MODEL DESCRIPTION AND DEVELOPMENT

### Background

FIRE-BGC is the union of the process-based, gap-replacement model FIRESUM (Keane et al., 1989, Keane et al., 1990a, Keane et al., 1990b) and the mechanistic biogeochemical simulation model FOREST-BGC (Running and Coughlan 1988, Running and Gower 1991). The mechanistic approach of FOREST-BGC improved the level of detail needed to understand those ecosystem processes that govern successional dynamics and to incorporate changes in atmospheric composition. FIRESUM's comprehensive simulation of forest dynamics in multi-species stands, and its integration of fire interactions with ecosystem components allow FIRE-BGC to simulate changes in species composition and abundance as a consequence of multiple disturbances over long time periods.

### FIRE-BGC Description

FIRE-BGC is a mechanistic, individual tree succession model containing stochastic properties implemented in a spatial domain. Tree growth, organic matter decomposition, litterfall and other ecological processes are simulated using detailed physical relationships. Tree establishment and mortality are modeled using probability functions with ecologically-derived parameters. FIRE-BGC also includes a spatial simulation of fire on the landscape and an assessment of the effects of fire on the ecosystem components.

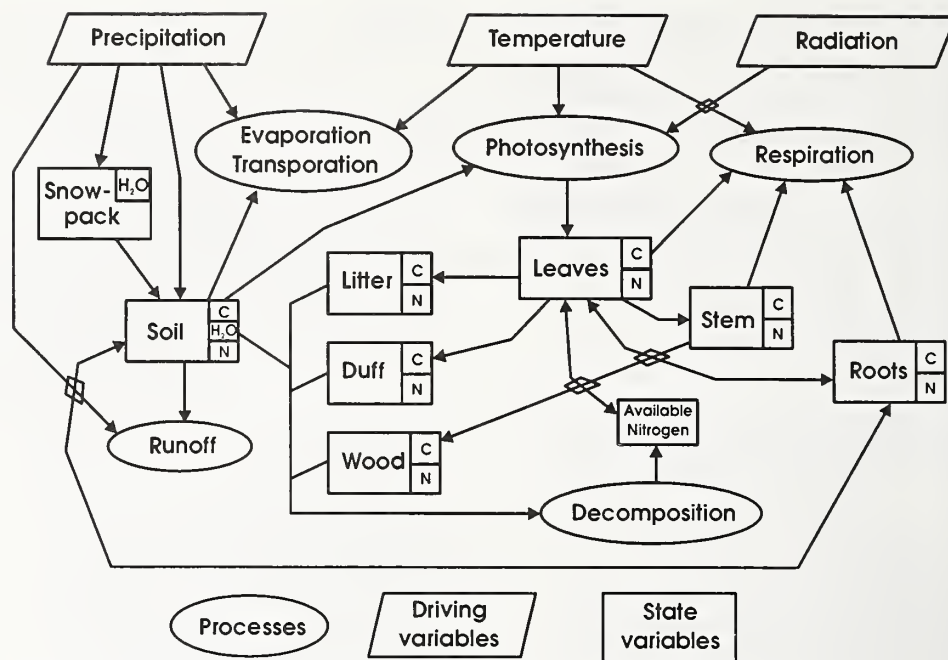


Figure 1.— Important ecosystem components simulated by FIREBGC.

Insect and disease interactions are also included in the model.

FIRE-BGC has a mixed time and space resolution built into the simulation design. Primary canopy processes of interception, evaporation, transpiration, photosynthesis and respiration are simulated at a daily timestep at the stand-level. Driving variables for these processes are taken from daily weather data. Annual carbon and nitrogen gains computed daily for each stand are allocated to each tree in the stand at the end of the year. Carbon and nitrogen allocated to each tree are then apportioned to the stem, roots and leaves. Allocation of carbon to the stem of a tree is used to calculate a corresponding diameter and height growth.

### FIRE-BGC Design

FIRE-BGC models the flow of carbon, nitrogen and water across

various ecosystem compartments to calculate tree growth. The major compartments and processes simulated by the model are diagrammed in figure 1. Carbon is fixed by tree leaves (i.e., needles) via photosynthesis using solar radiation adjusted for canopy depth and precipitation inputs, and this carbon is then distributed to leaves, stems and roots. A portion of the leaves, stem and roots are lost each year and accumulate on the forest floor in the woody fuel, litter, duff and soil (fig. 1). These forest floor compartments lose carbon through decomposition. Nitrogen is cycled through the system from the available nitrogen pool. The amount of carbon in each woody fuel compartment is converted to fuel loadings to predict fire behavior at the site. The weather conditions at the time of fire are taken from daily weather data specified by the user.

## Organizational Scales

There are five levels of organization explicitly recognized in FIRE-BGC (fig. 2). The coarsest level is the simulation **landscape** defined as a large expanse of land (greater than 10,000 hectares) delineated by the natural boundaries that control the major

properties of that ecosystem. These properties include climate, vegetation and disturbance. This landscape is divided into units of land called **sites** that have similar topography, soils, weather and potential vegetation. The boundaries of each site are static and do not change in a FIRE-BGC simulation.

The third level of organization is the **stand**. Each site is composed of a number of stands that are delineated by successional stage (i.e., different vegetation composition and structure) (fig. 2). By definition, stand boundaries cannot extend past site boundaries. However, stand boundaries are not stationary in FIRE-BGC. Processes of succession, fire and pathogens serve to alter stand boundaries within a site.

FIRE-BGC does not explicitly model all entities across the spatial extent of an entire simulation stand because of computational limitations. Instead, the model simulates ecosystem processes in a small portion or "vignette" of the stand called the simulation plot (fig. 2). Simulation plot size is input to FIRE-BGC and can be adjusted to improve computation time or ecological conditions.

The fourth organization level is the **species** level. Any number of species can inhabit a stand. Many modeled processes, such as canopy dynamics, are performed at the species level. The finest level of organization is the **tree** level (fig. 2). Each tree within a simulation plot is explicitly modeled in the FIRE-BGC architecture but these trees are not spatially defined.

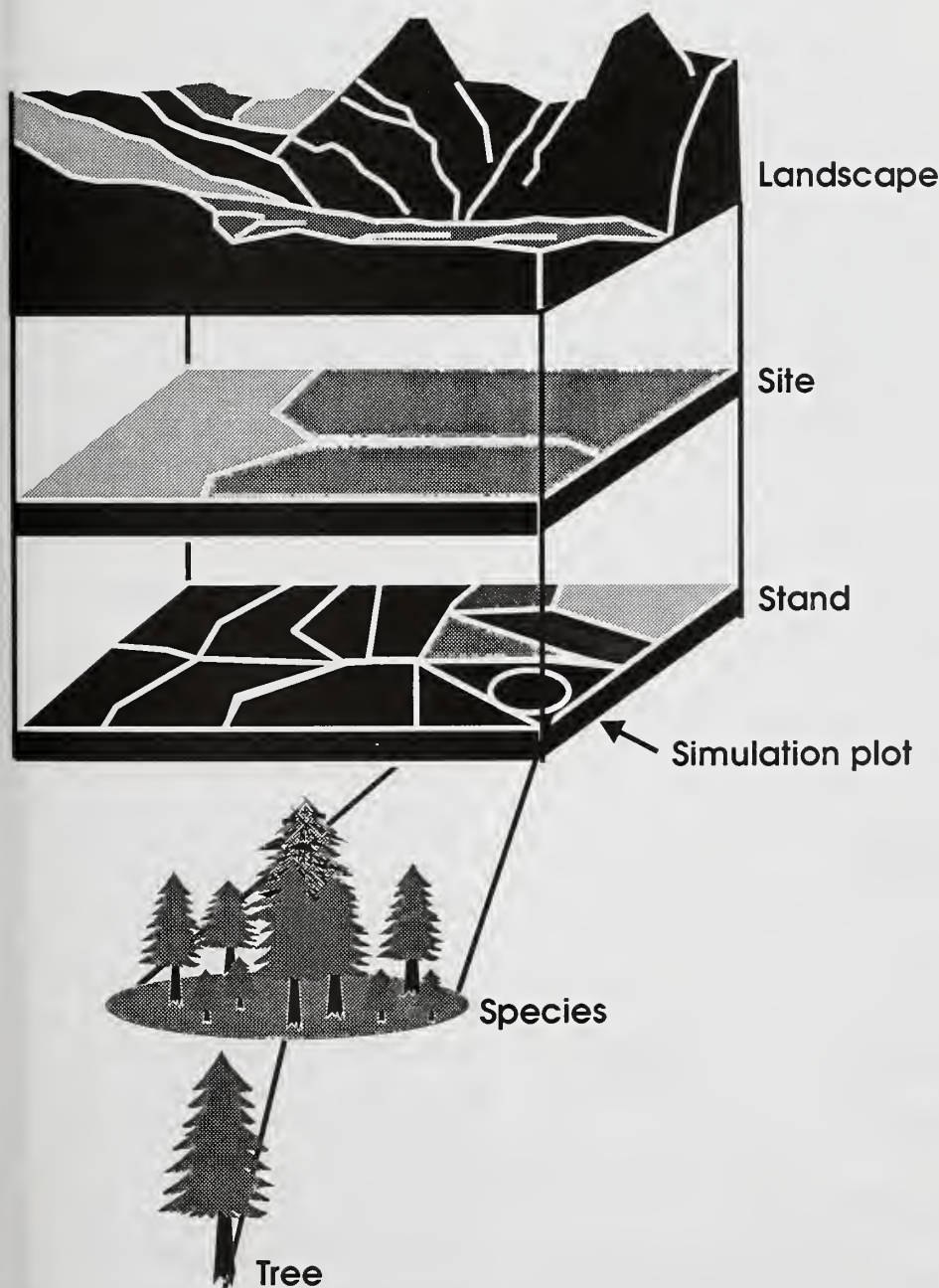


Figure 2.—Organizational levels recognized in FIREBGC.

## FIRE-BGC Implementation

FIRE-BGC was written in the C programming language using a modular approach where each organizational level implemented in the model was developed in separate components. The program was implemented on a SUN Sparc Model 10 workstation and accesses several software packages during execution.

## The FIRE-BGC Application

### Loki Modeling Platform

The Loki modelling architecture is used to link and schedule execution of the FIRE-BGC program and associated models SEEDER (landscape seed dispersal model), MAPMAKER (an ecological mapping routine), FIRESTART (a stochastic fire occurrence simulator) and FARSITE (a spatially-explicit fire behavior model) at the appropriate time intervals (Bevins et al., 1994, Bevins and Andrews 1994) (fig. 3). Loki also provides FIRE-BGC and submodels a set of routines to query, modify and create digital landscape maps during simulation. The GRASS spatial GIS package is used for organizing, displaying and analyzing raster files created by MAPMAKER through Loki (USA

CERL 1990). All models are described in detail in Keane et al. (1995).

### Associated Models

The occurrence and points of origin of simulated fires are stochastically predicted yearly on the simulation landscape using the model FIRESTART (fig. 3). Fire is dynamically modeled on the simulation landscape using the FARSITE spatial fire model (Finney 1994). This model predicts fire intensity and rate of spread as it moves across a landscape (Rothermel 1972). The probability that a tree species will disperse seed to each simulation stand is computed by the model SEEDER (fig. 3). Data is shared across models using dynamic data bases.

## SIMULATION EXAMPLE

The McDonald Drainage of Glacier National Park, USA (MD-GNP) is used to demonstrate the capabilities of FIRE-BGC. MD-GNP is a long, narrow glaciated valley surrounded by rugged mountains. The watershed starts at the Continental Divide and ends in McDonald Lake (fig. 4). This 20,000 hectare landscape is unique in GNP because of its great diversity in vegetation, topography and climate. Two distinct fire regimes are evident on the MD-GNP landscape (Barrett 1986). Large, stand-replacement fires were most common over the last four centuries on moist MD-GNP sites with return intervals of 120-350 years (Barrett et al., 1991, Habeck 1970b). Some stands in the higher and drier areas of MD-GNP contain evidence of less severe, more frequent surface fires.

### Data Input Methods

Ecosystem attributes describing site and stand data layers were quantified from an extensive ecological inventory of MD-GNP performed during the summers of 1993 and 1994. Sites were primarily delineated as potential climax vegetation types (Pfister et al., 1977) using satellite imagery and plant autecology information (Kessell 1979, Habeck 1968, Habeck 1970a). Satellite imagery from a July 15, 1988 Thematic Mapper (TM) scene was classified to several forest, shrub, herb and rock land cover categories using an unsupervised approach with MD-GNP field data (White et al., 1995). This land cover classifica-

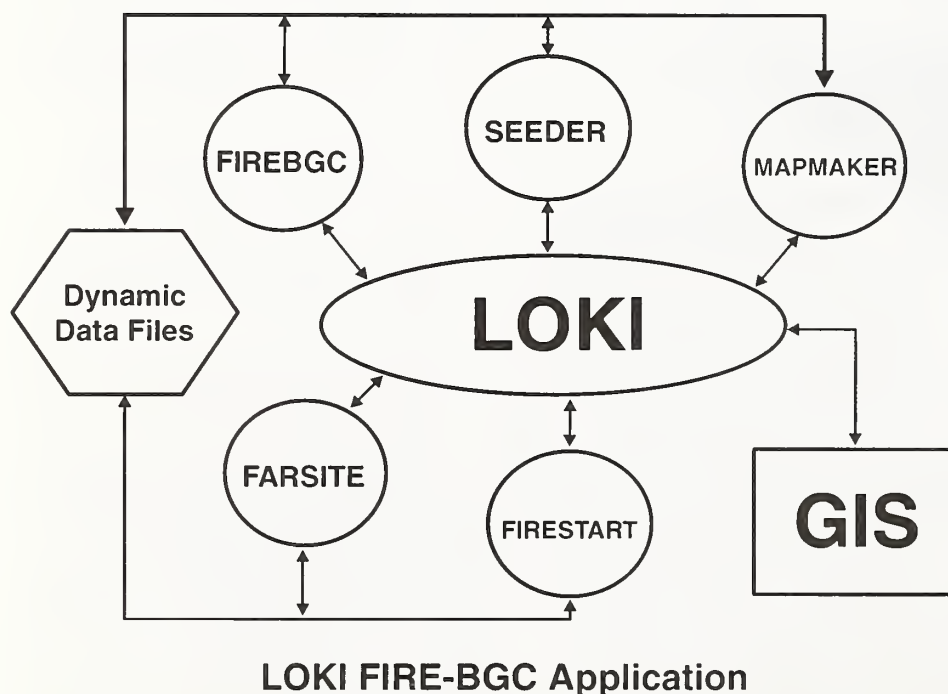


Figure 3.—Diagram of the LOKI modeling platform and the various models used in a FIRE-BGC application.

tion was used refine original site delineations.

A land cover type raster map of dominant vegetation was also created from the TM scene using a more detailed image classification. Field data and Kessell's (1979) gradient model were used to assign cover type descriptions based on the unsupervised spectral classification. This cover type raster map was combined with the site layer to produce a raster layer of stands hierarchically nested within the site layer.

Field data from plots representing these stands were entered into FIRE-BGC input files to quantitatively describe initial ecological characteristics. Tree age and size structure data measured on field plots representative of each cover type/site combination were entered into FIRE-BGC tree input tables for each stand. Most other stand level

input data such as fuel loadings and understory biomass were either quantified from field data or available literature (Habeck 1968, 1970a, 1970b).

## Simulation Methods

### Simulation Scenarios

Fire interactions in FIRE-BGC were initially tested using extremes in fire management scenarios. At one extreme was complete and successful suppression of all fires in MD-GNP (NOFIRE). At the other extreme, the fire regime that existed prior to European settlement (circa 1900) was simulated in FIRE-BGC (HISTFIRE).

Each scenario was simulated for 200 years using the same initial conditions at the start of model execution, and the same historical weather data set. No insect and

disease epidemics were simulated in this application.

## Results

### Fire Simulation

The FIRESTART model simulated the occurrence of two fires at simulation years 47 and 163. Fire spread and intensity predictions generated by the FARSITE model caused unique burn patterns. The crown fire in year 47 burned 4,321 ha (20% of MD-GNP) in hemlock-cedar forests at the northwestern end of MD-GNP. Predicted fire intensities ranged from 40 to 140,000 kW m<sup>-2</sup> and averaged approximately 1,496 Kw m<sup>-2</sup>. Then, a mixed, stand-replacement fire in year 163 burned about 5,187 ha (26% MD-GNP) in the subalpine fir forests of the upper, northeastern portion of MD-GNP. Fires were less intense (10 to 80,000 Kw m<sup>-2</sup>) and created a more complex pattern.

### Ecosystem Simulation

Landscape summary trend predictions for evapotranspiration (ET) are shown in figure 5 contrasting the two fire scenarios. Spatial distribution of ET (i.e., ET map) could not be presented in this paper due to the complexity of the maps but they are available from the authors.

### Model Validation

Measured ring widths from 10 trees for the last 40 years are compared with FIRE-BGC predicted tree ring widths in figure 6.

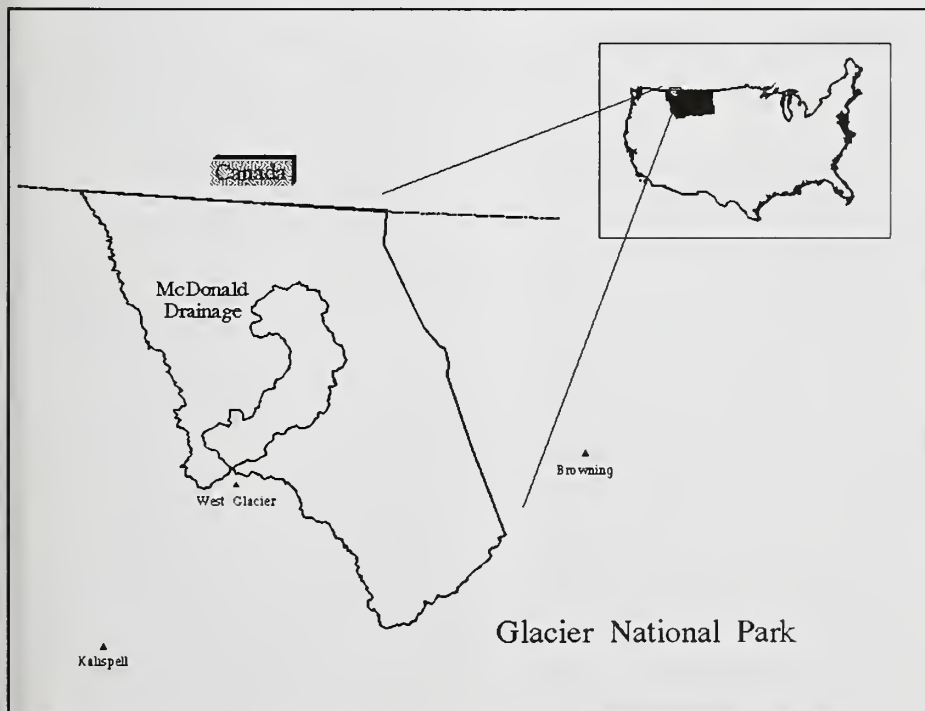


Figure 4.—McDonald Drainage Study Area, Glacier National Park, Montana, USA.

## DISCUSSION

### Model Limitations

FIRE-BGC is extremely difficult to initialize. The vast amounts and specificity of the input data needed to initialize model compartments precludes the use of field data to quantify all starting conditions. Regression equations provide efficient and economical estimates of initial tree components, but often do not account for biophysical influences on tree and stand characteristics. As a result, initial states of ecosystem compartments are in conflict with simulated ecosystem processes.

FIRE-BGC does not simulate undergrowth ecosystem processes at the detail provided for tree species. Consequently, processes such as NPP and ET are often underpredicted for early seral forest stands and perennial shrub and herb lands because of the

lack of trees in the stand. Undergrowth contributions to the forest floor are also overpredicted because there is no feedback to regulate growth based on environmental conditions.

FIRE-BGC does not adequately rectify life cycle characteristics of trees with ecophysiological dynamics of the stand. The link between tree regeneration, mortality and growth with stand carbon, nitrogen and water cycling needs a more comprehensive and mechanistic treatment in FIRE-BGC. Carbon allocation from the stand-level to individual trees needs improvement. Contributions of stand photosynthate production by trees of different species and sizes is a complex computation in the model.

Weather data record used for simulating MD-GNP ecosystem processes is probably not appropriate for long-term successional

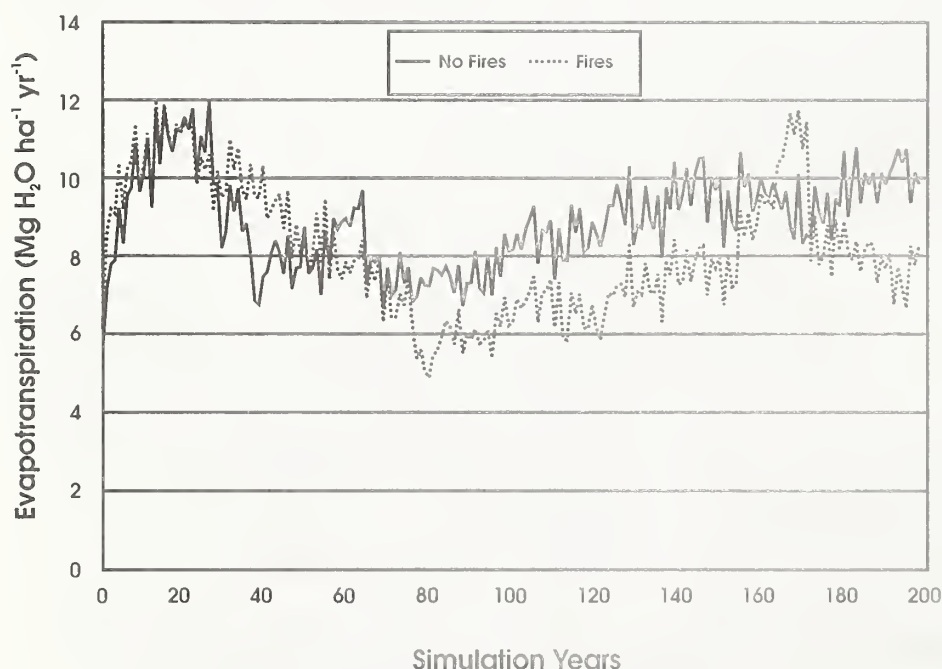


Figure 5.—Evapotranspiration ( $\text{Gg H}_2\text{O ha}^{-1} \text{ yr}^{-1}$ ) predictions over the 200-year FIRE-BGC simulation with and without fire.

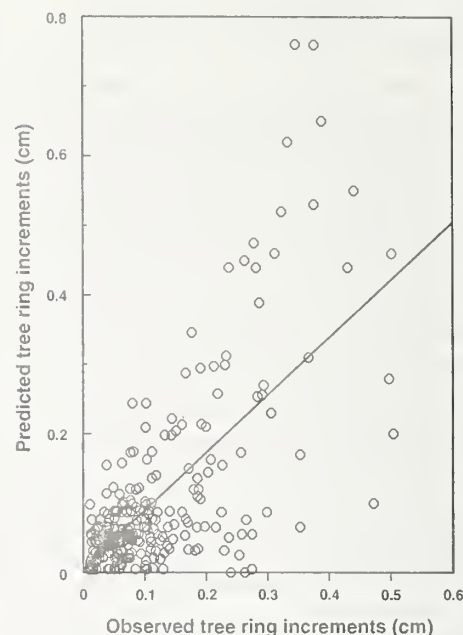


Figure 6.—Measured vs observed tree ring widths for 10 trees over 40+ years ( $R^2=0.89$ , slope=0.94, intercept=0.015).

modelling. First, the length of weather record (40 years) is too short for multi-century simulations. Some predicted ecosystem states respond closely with weather cycles and repeating short, 40 year weather cycles is not representative of the climate pattern that influenced ecosystem formation. Secondly, the raw weather data used in the simulation came from one weather station just outside drainage boundaries. Extrapolation of this data to the complex mountain terrain in the MD-GNP may not fully represent the true range of weather conditions that controlled vegetation development. Many local weather events such as cold air drainage, frost pockets and wind-funneling are not predicted by the MTCLIM weather model (Hungerford et al., 1985). Long-term weather records from many weather stations are needed for future long-term successional modelling in FIRE-BGC.

The topography of the Lake McDonald drainage is extremely complex. Elevation ranges from 1,000 to 3,500 meters. At the lower elevations the drainage is primarily oriented east and west and the valley floor is dominated by Lake McDonald. The upper half of the drainage is oriented north and south. The drainage is a steep glaciated valley. Rock walls and avalanche shoots routinely disrupt vegetation development. This and the influence of the drainage on local wind have resulted in a history of relatively small fires. As a result the pattern of stands in the drainage is extremely complex, somewhat chaotic. This complexity provides a rigorous test of fire spread and regeneration predictions.

### Future Research

We plan to use FIRE-BGC to investigate the cumulative effects of fires at many spatial and temporal scales. Effects of future climates on fire and vegetation will be examined for Glacier National Park. Changes in landscape pattern, structure and composition will be assessed over several centuries for the Bob Marshall Wilderness Complex. Prescribed natural fire programs for the Selway Bitterroot and Gila Wilderness areas will be evaluated using the model. Limits of an ecosystem's natural range of variability will be investigated for the Yellowstone Ecosystem. Lastly, conservation plans for declining whitebark pine forests will be designed from FIRE-BGC predictions.

FIRE-BGC algorithms will be continually modified and revised. Carbon allocation routines at the

stand and tree level will be refined from field study results. Tree regeneration and mortality components will also be expanded and improved. Fuel bed parameters will be fine-tuned to give better predictions of fire behavior. Undergrowth dynamics will be more mechanistically driven, and scaling factors will be added to evaluate model results across scales.

### CONCLUSIONS

FIRE-BGC is the results of our initial attempts to develop a climate-sensitive mechanistic process model that realistically incorporates disturbances at the landscape scale. This succession model is still in the developmental stage and many model process algorithms and parameters need improvement. However, general trends predicted by the model seem reasonable.

### ACKNOWLEDGEMENTS

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# Effect of High CO<sub>2</sub> on Cold Acclimation and Deacclimation of Three Conifers<sup>1</sup>

Richard W. Tinus,<sup>2</sup> Dennis H. Greer,<sup>3</sup> and Linda A. Robinson<sup>3</sup>

**Abstract.**—Seedlings of three conifers were cold hardened and dehardened in growth rooms under 350 or 700 ppm CO<sub>2</sub>. High CO<sub>2</sub> had little effect on cold hardiness of radiata pine, but increased autumn and spring hardiness of Douglas-fir. High CO<sub>2</sub> increased hardiness of ponderosa pine in autumn and decreased it in the spring.

## Introduction

Atmospheric CO<sub>2</sub> levels are rising, and whether or not this leads to a climate change, high CO<sub>2</sub> is known to have some direct effects of plants. One aspect that has only begun to be explored is possible effects on cold hardiness. Well adapted woody plants can tolerate the lowest temperatures to which they may be exposed at all times of the year. Every year temperate and boreal woody plants must cold harden in a timely manner in autumn, become hardy enough to withstand the coldest winter temperatures, and not lose their hardiness prematurely in the spring.

Our objective was to determine the effect of elevated CO<sub>2</sub> on cold acclimation and deacclimation of three commercially important conifers.

## Materials and Methods

*Pinus radiata* D. Don, *Pinus ponderosa* var. *scopulorum*, Engelm. and *Pseudotsuga menziesii* var. *glauca* (Beisn.) Franco were grown from seed in a greenhouse at the Hort+ Research Institute, Palmerston North, New Zealand. When they reached an adequate size, they were moved into two controlled environment rooms at the NZ National Climate Laboratory, one room with 700 ppm atmospheric CO<sub>2</sub> and the other at approximately 350 ppm. To minimize any equipment or position effects, each week the treatments and trees were rotated between rooms and the trees within rooms randomized. To simulate an autumn, winter, and spring, the following regime was imposed:

4 weeks 8 hr day 20°C, night 15°C, then

6 weeks 8 hr day 10°C, night 3°C, then

5 weeks 8 hr day 3°C, night -1°C, then

5 weeks 12 hr day 10°C, night 3°C, then

5 weeks 16 hr day 22°C, night 17°C

Water vapor pressure deficit was 0.3-0.5 kPa, and photon flux density was 700  $\mu\text{mol m}^{-2}\text{s}^{-1}$  provided by a water screened array of metal arc and tungsten halogen lamps, except at the lowest temperature where intensity was 350  $\mu\text{mol}$ .

Cold hardiness was measured weekly by freeze induced electrolyte leakage (FIEL). Whole plant freeze tests were made at less frequent intervals and used to calibrate FIEL. For each treatment a 50% index of injury and its 95% confidence interval were calculated. When the 95% confidence intervals of the high and low CO<sub>2</sub> treatments did not overlap, they were considered significantly different.

## Results and Discussion

Starting in a late summer condition at minimum cold hardiness, all three species hardened during the first three regimes, but to different maxima, as expected for species native to quite different habitats (fig. 1). First order examination showed little consistent difference between the high and low CO<sub>2</sub> treatments, however, when the low CO<sub>2</sub> 50% index of injury temperature was subtracted from that of the high CO<sub>2</sub> treatment, some

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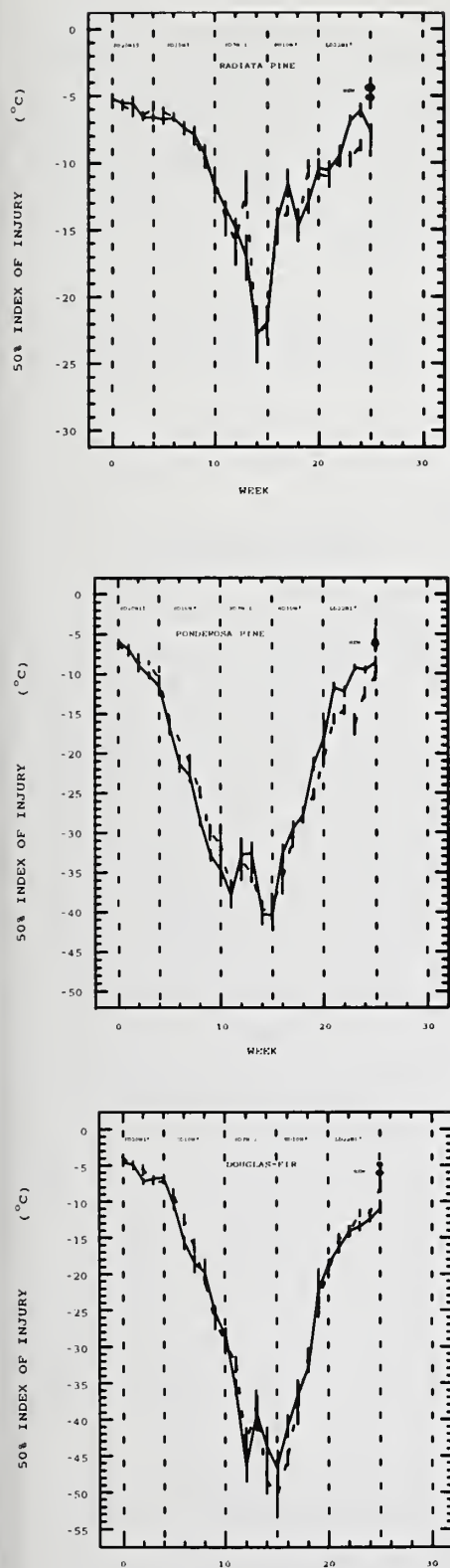


Figure 1.

differences appeared that may be important. In figure 2 significant differences are indicated by solid squares and a positive difference means that the high  $\text{CO}_2$  trees are harder than the low  $\text{CO}_2$  trees.

Radiata pine showed no trend in significant differences during the 25 week experiment (fig. 2A). One observation at week 13 seems aberrant, but no reason to doubt its authenticity has surfaced. It may be an example of "hunting" behavior common to unstable systems and shown more clearly by ponderosa pine and Douglas-fir.

Of the three species, ponderosa pine showed the most clear cut differences between  $\text{CO}_2$  treatments (fig. 2B). Much of the time during acclimation the high  $\text{CO}_2$  trees were 2-4°C more hardy than those in the ambient  $\text{CO}_2$  treatment. However, the reverse was true during deacclimation.

Behavior of Douglas-fir was different yet (fig. 2C). Like ponderosa pine, during acclimation the high  $\text{CO}_2$  trees were harder than under low  $\text{CO}_2$ . At maximum hardiness the reverse was true by about 4°C, but during deacclimation as the trees approached minimum hardiness, the high  $\text{CO}_2$  trees were again more hardy than the low  $\text{CO}_2$  trees.

### Conclusions

The results presented here must be treated with caution because the seedlings were all grown to useable size in a greenhouse under ambient  $\text{CO}_2$  and placed in their experimental treatments only when the acclimation regime began. Therefore, we cannot rule out the possibility

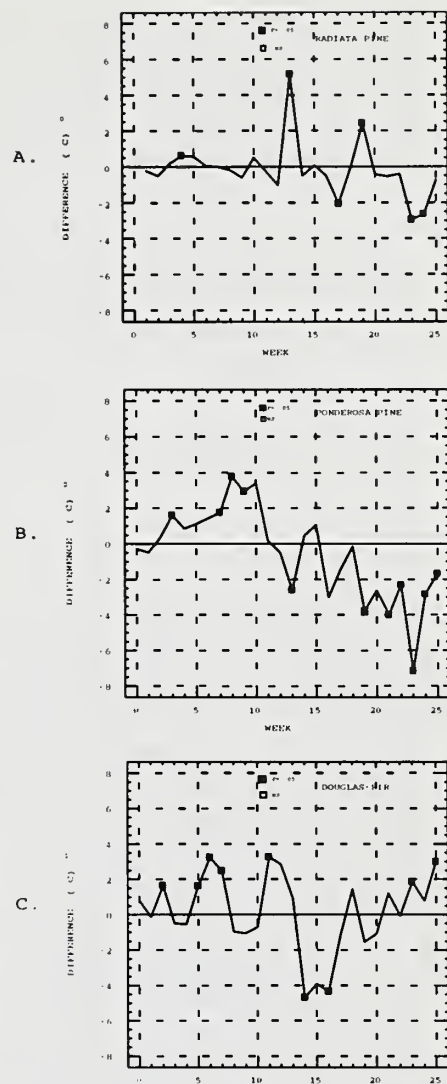


Figure 2.

that there was a carryover effect on the development of cold hardiness that was not detected. However, to the extent that this experiment mirrors cold acclimation and deacclimation in the real world we can conclude that:

- 1 The three species behaved quite differently, which makes it hard to generalize and suggests that there is a lot more to be learned about other species.

- 2 High CO<sub>2</sub> had no consistent effect on cold hardiness of radiata pine. That is good news for the Southern Hemisphere.
- 3 High CO<sub>2</sub> had a predominantly beneficial effect on ponderosa pine in the autumn, but could render it more susceptible to spring frosts. However, the increase in temperature expected from climate change may compensate for this effect.
- 4 High CO<sub>2</sub> would benefit Douglas-fir in the autumn and spring. Loss of some hardiness at mid winter is probably not important, since well adapted trees almost always have greater maximum hardiness than is needed. Coupled with a warmer climate, this suggests that Rocky Mountain Douglas-fir could be a favored species up to its present upper elevational limit, and may be adapted at even higher elevation in the future.

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# Preliminary Results of Carbon Cycling in Southwestern Ecosystems: Implications for Climate Change<sup>1</sup>

Carole Coe (Klopatek,<sup>2</sup> Kenneth L. (Murphy,<sup>3</sup> and Jeffrey M. (Klopatek<sup>3</sup>

**Abstract.**—By determining the C pool sizes, cycling and relative sequestering rates, we intend to estimate what the effects of a vegetation change caused by a temperature increase and available moisture decrease. A predominant source of C for the soil compartment is the plant litter and its subsequent decomposition. The resulting effect of temperature and moisture on decomposition will vary according to the biome and litter quality of that biome. Litter quality, referring to the carbon and other nutrient fractions, strongly influences the potential rate of decomposition. Our preliminary findings indicate that litter quality and moisture, not temperature, are the major controlling variables in decomposition.

## INTRODUCTION

Current projections suggest a global warming between 1.5 and 4.5°C in the coming century (IPCC estimates, Mitchell et al, 1990, Schneider 1989). A potential global climate warming may seriously affect the arid and semi-arid southwestern United States as researchers forecast a 17% increase in the desert land area (i.e. desertification) (Emanuel et al. 1985). In spite of high variability in predicted rainfall, soil moisture is anticipated to decrease in most of the region (Manabe and Weatherford 1987, Washington and Meehl 1989). The effects of a temperature increase and soil moisture depletion may have profound consequences on the productivity, diversity, and extent of natural resources in this region resulting in major shifts in vegetation

types. Schlesinger et al. (1990) suggests that climate warming may cause significant changes in global biogeochemical cycles that are further disrupted by positive feedbacks, resulting in a shift from semi-arid to arid systems. Thus, these predicted changes by climate change will have an effect on vegetation types and carbon storage and flux rates in southwestern ecosystems.

Problems of global change require that analyses and predictions be developed for very broad scales. A successful approach appears to be the evaluation of broad-scale environmental gradients that occur over a region and the identification of boundaries that occur in the relatively steep portions of those gradients. However, at the scale of regions, environmental boundaries are likely to be defined by biomes or dominant life-forms. These transitions between different biome or ecosystem types are a function of a wide range of processes which operate on many time and space scales. The environmental driving functions causing gradients are likely to exercise significant control on ecosystem level processes (e.g.,

primary productivity, nutrient cycling) (NATO, 1993, Risser 1995, Turner 1989). Resource dynamics and resource limitations for commodities such as water and nutrients often significantly differ between biomes or in transition zones. Thus, the relationship between vegetation and climate is symbiotic, but not exclusive as soils, fauna and human activities all impact vegetation (Klopatek et al. 1992, Riebsame et al. 1994).

For arid or semi-arid biomes, there appears to be a continuous change in species composition from the core to the edges, although plant life-form appears to be a more uniform characteristic over the larger area. These structural differences are often accompanied by distinct differences in C pools and partitioning of resources. Structural properties of plants markedly effect ecosystem properties at all scales. For example, structural differences in leaves between grasses, shrubs and trees affect nutrient cycling and decomposition rates. Presence of woody shrubs and trees affects properties such as ecosystem biomass, nutrient storage and microclimate. Since species move

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about individualistically in the face of climate changes (Davis 1981), studies of change need to be conducted at multiple spatial scales in order to anticipate the changes that also occur at multiple temporal scales.

The intent of article is to provide a brief overview of our research examining the consequences of global change in the southwestern ecosystems. Over the past 3 1/2 years, the major part of our research has focused on how potential climate change may affect C pools and fluxes. We are documenting the relative pool sizes and aggradation rates of C as they change across the ecotonal boundaries from one system to another. We have been concentrated our efforts along an environmental gradient in northern Arizona, starting from Great Basin shrubland through a pinyon-juniper woodland, up to ponderosa pine forest. This area demonstrates

distinct structural and physical properties as mentioned above. In addition, it has a temperature gradient of approximately 3°C. As shown in figure 1, mean site differences are a result of minimum temperatures which have been predicted to be most affected by climate change. Thus, this area offers a unique system in which to evaluate questions of landscape dynamics and scale. Studies of multiple scales are needed because they will reveal the interaction between data collected and the interpretation of the data relative to the question of hierarchical level: the patch, community, biome. Scale dependent concepts, such as species, community, and biome indicate that a multi-scale approach need be developed to separate out the possible changes, due to factors that operate on different time scales (Henderson-Sellers and McGuffie 1995, Schimel 1995) and between different levels in the hierarchy

(O'Neill 1988). Thus, after the first phase of the research is completed (i.e., documenting the differences in pool sizes and ecosystem properties at the scale of selected sites), we will enter the next phase of predicting changes at the regional biome scale under more stressful conditions resulting from climate changes. Below, we discuss one specific aspect of this research, evaluating how decomposition is influenced by differences in climate and carbon quality.

## MATERIALS AND METHODS

### Site Description

The study area is located in the Coconino National Forest, due north of Flagstaff, Arizona. Within this area we have chosen five study sites that occur along a 7.5 km environmental gradient ranging along: (1) a Great Basin Desert scrub (DS); (2) a transition zone from desert scrub to pinyon-juniper (DS-PJ); (3) a pinyon pine-juniper woodland (PJ); (4) a second transition zone from pinyon-juniper to ponderosa pine (PJ-PP); and (5) a ponderosa pine site (PP). Average temperatures for 1993 are given in figure 1.

All sites were chosen so that geological, topographic, and edaphic differences were minimized. Aspects of the sites range from 20° to 130° with slopes from 2% to 5%. The soils at all sites are derived from volcanic material and are classified as Typic Agri-borolls at the upper elevations and grading through Aridic Argiustolls and into Haplastolls at the lower elevations. The soils are all silty clay loams and are slightly basic to slightly acidic.

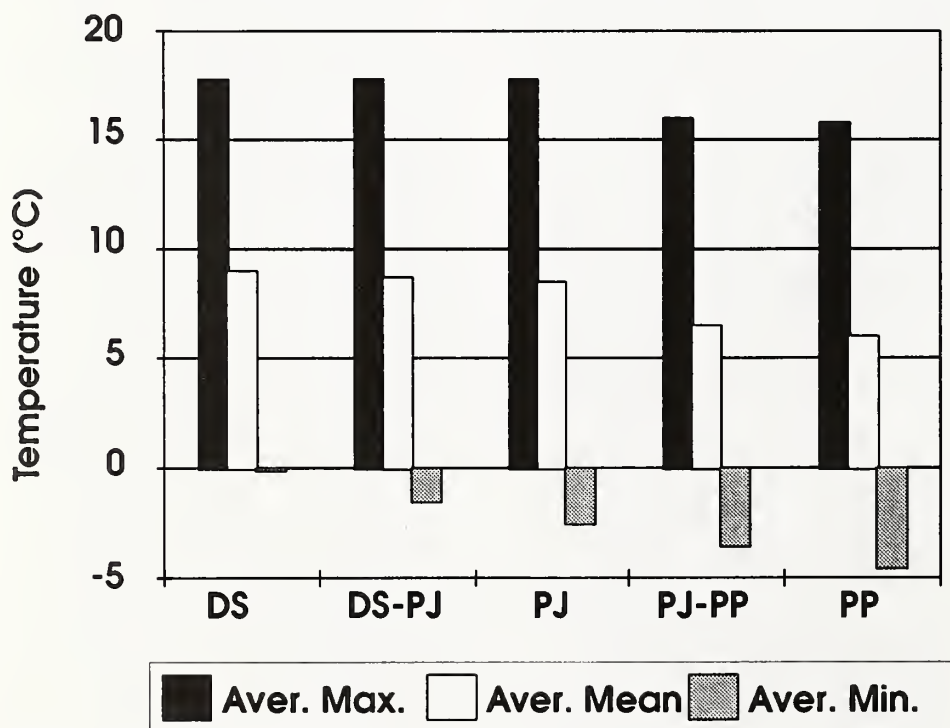


Figure 1.--Average temperatures at each site.

## Experimental Design

In late fall of 1993, a litter bag decomposition experiment was established using abscised needle litter collected from ponderosa pine (PIPO), pinyon pine (PIED), one-seeded juniper (JUMO), and blue grama grass (BOGR) and both dead leaves and stems from snakeweed (GUSA). Each litter type was separated from any foreign material and thoroughly mixed to ensure the purity and homogeneity of the samples. In order to understand how climate effects decomposition, litter was swapped along the gradient. Litter bags containing BOGR, PIED, and JUMO were placed at all five sites. GUSA was placed at the lower three sites (DS, DS-PJ, and PJ) and PIPO was placed at the upper three sites (PJ, PJ-PP, and PP). Litter bags were placed in the interspaces at each site to reduce any variability of microclimate and nutrient effects between canopies and interspaces. Upon collection, litter bags were placed separate paper bags and transported on ice in a cooler back to the laboratory. Mass loss of litter

was determined by weighing litter bags and determining net loss, and ashing subsamples to correct for soil contamination.

## Laboratory Analysis

### Soil Analysis

Soils were analyzed for several chemical and physical properties. Soils were dried at 60°C for 48 hours and sieved through a 2-mm mesh sieve. The pH's were measured using a 1:1 soil slurry with distilled water (Allen, 1989). Soil organic C was determined using a modified method of the Walkley-Black procedure (Jackson 1958). Listed in table 1 are the pH values and organic C content of soils from each site.

### Leaf Litter Carbon Fraction Analysis

Samples were analyzed for Klason lignin, cellulose and total carbohydrates. Oven dried litter samples were milled through a 40-mesh screen and then vacuum dried at 45°C. Approximately 200

mg of the sample was hydrolyzed with 2.00 ml 72% (w/w) H<sub>2</sub>SO<sub>4</sub> for 1 hr at 30°C. Samples were then diluted to 4% (w/w) H<sub>2</sub>SO<sub>4</sub> with distilled water, fucose added as an internal standard, and a secondary hydrolysis performed for 1 hr at 121°C. Following secondary hydrolysis, samples were immediately filtered through tared crucibles containing glass fiber filters. The filtrate and three washes with 5 ml distilled H<sub>2</sub>O were collected in 100 ml volumetric flasks. The acid-insoluble residue (Klason lignin) was washed an additional six times with 10 ml hot distilled H<sub>2</sub>O and quantitated gravimetrically. Sugar content of the hydrolysates were determined by anion exchange high performance liquid chromatography using pulsed amperometric detection.

### Statistical Analysis

Mass loss data were analyzed using ANOVA with LSD with SAS (1989) statistical program. It is our intent to evaluate each of the significant parameters (i.e., climate, chemical, physical and biological) that regulate decomposition. These parameters will be used to construct a decomposition model for these predominant semi-arid southwestern ecosystems.

## RESULTS AND DISCUSSIONS

### Mass Loss and Litter Quality

The effects of climatic factors (i.e., temperature and moisture) on the rate of decomposition are presented in figure 2. After 16 months, overall mass loss data

Table 1.—Chemical analysis of soils across the gradient. OC = % organic carbon.

	Site									
	Desert shrubland		DS-PJ		Pinyon-juniper		PJ-PP		Ponderosa pine	
	pH	OC	pH	OC	pH	OC	pH	OC	pH	OC
Interspace	7.17	1.37	7.45	1.13	7.23	0.63	7.18	1.10	5.57	2.26
Juniper	*	*	8.29	1.18	8.28	1.18	7.97	1.40	*	*
Pinyon pine	*	*	-	1.2	7.2	1	7.3	1.7	*	*
Ponderosa pine	*	*	*	*	*	*	6.60	1.63	5.9	1.7

\*Species does not occur.

reveals that the rate of decomposition for the three common species along the gradient (BOGR, JUMO, and PIED) was significantly greater at the two upper elevational sites as compared to the two lower sites (fig. 2). This corresponds with the level of actual evapotranspiration (Meentemeyer 1978) at the higher elevational sites, although temperature decreased. We anticipate that this result will be maintained, particularly through the warmer, dry periods. The rate of decomposition was not significantly different between the DS and DS-PJ sites or significantly different between the two upper sites, PJ-PP and PP. At the PJ site there were no differences between overall mass loss and either the two upper or two lower elevational sites. This information substantiates our earlier contentions that PJ, with its different physiognomic and edaphic

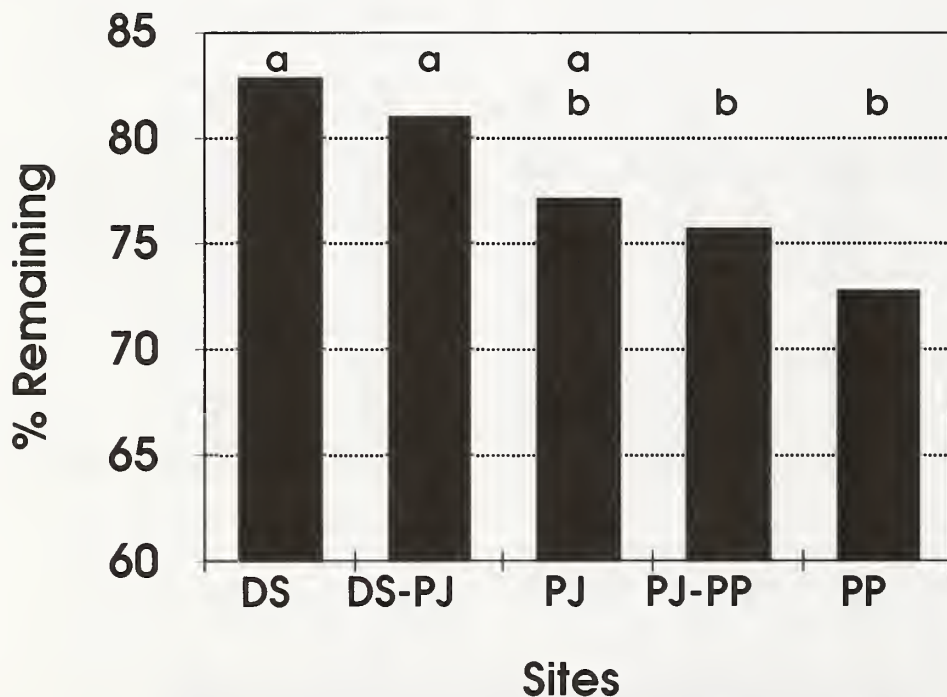


Figure 2.--Average mass remaining at five sites, for three litter types, after 16 months.

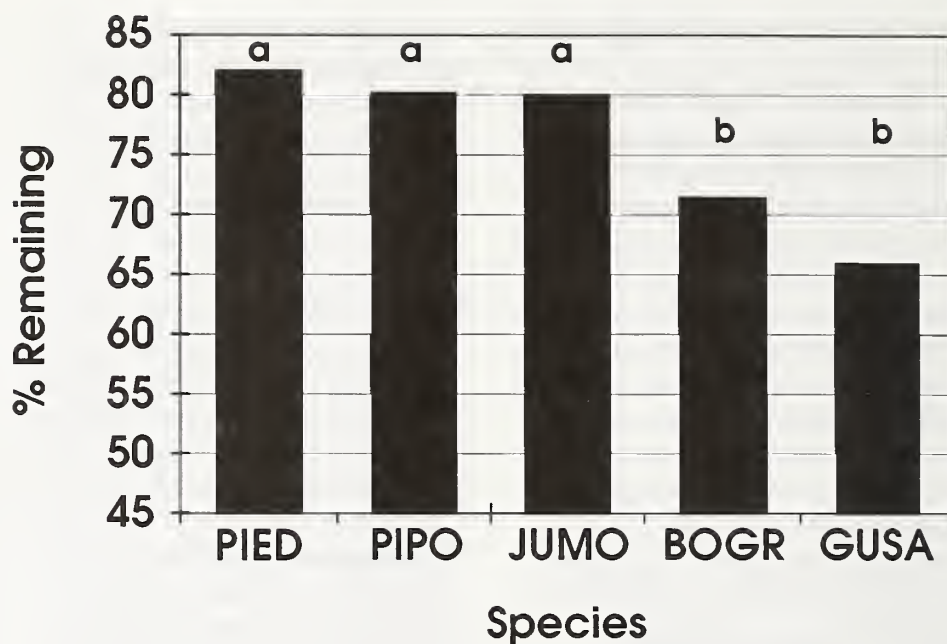


Figure 3.--Average mass remaining for five litter types, after 16 months.

physiographic and climate characteristics, is truly and ecotonal area between mesic (PP) and xeric (DS) ecosystems (Klopatek, 1987, Klopatek et al. 1988,1990, Klopatek and Klopatek, 1995). Thus,

it has the potential to demonstrate a large range of environmental changes such as one that may come about as a result of climate change.

In examining all the different species, BOGR and GUSA decompose significantly faster than any of the tree species, particularly at the upper sites in which they were placed along the gradient (fig. 3). These results may be explained by their higher litter quality. Table 2 is a partial list of some of the litter quality elements that we have examined. Thus far, we have found that BOGR and GUSA have a significantly greater fraction of C in sugars and cellulose compared to lignins. Whereas, all the tree species have a significantly greater proportion of their C tied up in lignins which are of lower quality and slower to decompose (table 2). Studies have shown that lignin content alone of the litter has been shown to have the greatest influence on the rate of decomposition (Mc-

Table 2.—Carbon fractions of the five litter types prior to decomposition. Key: KL = Klason Lignin; ASL = Acid Soluble; CEL = Cellulose; Arab = Arabinan; Rham = Rhaman; Gal = Galactan; Glu = Glucan; Xyl = Xylan; Man = Mannan; TL = Total Lignin; Lignin:Carbohydrate ratios determined by Raman Spectroscopy; TS = Total Sugars; values are gm/l gm, TL:CELL = Total Lignin:Cellulose ratio.

	Chemical Analysis										TL	TS	TL:TS	TL:CELL
	%KL	%ASL	%CEL	%Arab	%Rham	%Gal	%Glu	%Xyl	%Man					
BOGR	27.7	3.2	31.6	3.5	0.08	1.44	31.71	18.23	0.44	30.9	55.4	0.56	0.98	
GUSA	26.3	4.2	25.47	1.8	0.6	1.4	25.7	14.1	0.7	30.5	44.3	0.69	1.20	
JUMO	37.2	4.2	16.73	5.2	0.6	2.2	17.5	1.8	2.3	41.4	29.6	1.40	2.47	
PIED	41.6	3.9	16.60	3.9	0.5	2.3	18.3	1.4	5.1	45.5	31.5	1.44	2.74	
PIPO	40.7	3.0	19.50	3.2	0.5	2.4	21.2	2.8	5.1	43.7	35.2	1.24	2.24	

Claugherty et al. 1985, Berg and Ekbohm 1990). At the lower three sites (DS, DS-PJ, and PJ), initial lignin concentrations from all litter samples are inversely related to the resulting decomposition rate. BOGR has the lowest lignin concentration and is subsequently decomposing more rapidly than GUSA, JUMO, PIED and PIPO, respectively. Thus, at these lower sites, lignin may be a fair indicator of decomposition.

We view these preliminary findings as interesting differences in ecological processes that may be influenced by future climate changes. The initial results suggest several different scenarios for changes in carbon fluxes given a temperature and moisture change. We report indications of trends; however, the evidence on how climate, litter quality and bacterial activity affect decomposition will become more apparent as this research progresses.

### Concluding Remarks

The dynamics of biogeochemical cycling of C depends on the rate of the processes that control storage in, and transfer between, the

various reservoirs. The dynamics and thus, the response of C cycling to disturbances such as grazing, climate change etc. are also complicated by the coupling of other biogeochemical cycles (e.g., N) and numerous positive feedback mechanisms. For example, a recent terrestrial model intercomparison (Vegetation and Ecosystem Modeling and analysis Project: VEMAP, 1995) illustrated that unless N fixation responses to increased CO<sub>2</sub> are strong and ubiquitous, direct effects of CO<sub>2</sub> on carbon storage will be less than leaf-level effects by 50% or more. Although these comparisons were calculated on a continental scale, it emphasizes the critical need in the understanding of the dynamics and feedbacks that occur in C and N cycling in these systems since little baseline information currently exists. This lack of information hampers the development of predictive models (NATO, 1993). Thus, by examining how nutrient acquisition, cycling and turnover affects site productivity we will attempt to improve predictions on how future anthropogenic disturbances (i. e. climate change) affect landscapes in southwestern ecosystems.

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# Spatial and Temporal Patterns in Water Chemistry of Two High Elevation Lakes in Southeast Wyoming<sup>1</sup>

Robert C. Musselman<sup>2</sup>

## Introduction

The Glacier Lakes Ecosystem Experiments Site (GLEES) was established to examine the effects of atmospheric deposition and climate change on alpine and subalpine ecosystems. The site contains East Glacier Lake (3282 m elevation) and West Glacier Lake (3276 m elevation), and their watersheds. These two small lakes are located 120 m from each other at the alpine/subalpine transition. The lakes are similar in surface area, depth, and volume, but differ in watershed size, flow patterns of input, and water chemistry (Musselman 1994). Water chemistry has been monitored on these lakes periodically since 1987. Preliminary data indicate that they are subject to acidification (Reuss et al 1993, Reuss 1994).

This report documents temporal and spatial trends during 1993 in water chemistry in East and West Glacier Lakes. Data are presented on seasonal and lake depth changes in water chemistry of the two lakes. The application

of the results to appropriate sampling protocols for alpine lakes is discussed.

## Methods

Samples were collected at the deepest portion of each lake as determined from bathymetric maps. Water was collected from a small boat in summer, and through a 20-cm diameter augured hole in the ice in winter, using a peristaltic pump to draw water from the sampling depth to sample bottles. Samples were collected at 0.5 m from the surface and thereafter at 1.0-meter intervals from the top to the bottom of the water column. In addition, integrated samples were collected from each lake after column sampling, by collecting water in a 1.0 l container as the sample tube was pulled slowly through 1-2 complete cycles from the top to the bottom of the lake. The lakes were resampled at approximately monthly intervals. Both lakes were sampled during the same day, at midday. Samples were kept cool, returned to the lab the same day, and filtered for analysis. Samples were analyzed for cations and anions, pH, and conductivity at the Rocky Mountain Station Water Chemistry laboratory. Silica and aluminum

were also measured for some sample dates. Appropriate blanks, duplicates, and blind samples were collected for analysis. Data were analyzed separately for each lake using the SPSS MANOVA program, with lake depth and date of sampling as the sources of variation. Depth by date interaction was also examined.

## Results and Discussion

Results indicate that water chemistry in both lakes showed significant variation with both lake depth and season (table 1). Both depth in the lake, and date sampled were highly significant sources of variation for almost all water chemistry variables examined. Interaction (date by depth) was also significant for most variables. The data confirmed that the lakes stratify, then mix, at various times during the season. The lakes generally stratify under ice cover, mix at snowmelt, then stratify again during the late summer, early fall.

## East Glacier Lake

Nitrate and phosphate levels were generally below detection limits, except for a brief period at

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Table 1.—MANOVA Significance of F value.

Source	Variable													
	Cond	Ca	Mg	Na	K	NH <sub>4</sub>	Cl	NO <sub>3</sub>	SO <sub>4</sub>	PO <sub>4</sub>	pH	ANC	Al	SiO <sub>2</sub>
<b>East Glacier Lake</b>														
Depth	0.00	0.00	0.00	0.00	0.002	0.347	0.124	0.008	0.00	0.08	0.167	0.00	0.380	0.001
Date	0.00	0.00	0.00	0.00	0.000	0.022	0.000	0.000	0.00	0.00	0.000	0.00	0.211	0.004
DepthxDate	0.00	0.00	0.00	0.00	0.000	0.235	0.041	0.000	0.00	0.00	0.307	0.00	0.873	0.009
Model	0.00	0.00	0.00	0.00	0.000	0.049	0.000	0.000	0.00	0.00	0.000	0.00	0.344	0.000
<b>West Glacier Lake</b>														
Depth	0.00	0.00	0.001	0.545	0.00	0.00	0.001	0.613	0.026	0.00	0.821	0.012	0.252	0.165
Date	0.00	0.00	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.002	0.000	0.954	0.000
DepthxDate	0.00	0.00	0.000	0.981	0.00	0.00	0.005	0.000	0.250	0.00	0.075	0.000	0.008	0.278
Model	0.00	0.00	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.014	0.000	0.171	0.000

the lake surface during snowmelt. The low nitrate and phosphate levels indicate that the deposition load is below the saturation level at this site. The lake was stratified in winter, and became mixed at snowmelt in the spring. The bottom meter of the lake became anaerobic in winter, with higher concentrations of the base cations Ca, Mg, and K, lower concentration of SO<sub>4</sub> anion, lower pH, higher alkalinity and conductivity at the bottom of the lake. Conductivity and alkalinity remained relatively constant throughout the summer. Seasonal change in pH was minimal, with a pH range of only about 0.5 pH units throughout the year. Lowest pH occurred at the bottom of the lake in winter, but never decreased below pH 6.3. Only a slight decrease in pH occurred at snowmelt. Secchi depth (data not shown) was deep during most of the year, with the lake bottom (7 m) visible during much of the year. The base cations Ca, Mg, Na, and K remained relatively low after snowmelt input. Sulfate, the major detect-

able acid anion, remained relatively low in concentration throughout the year. A slight decrease in sulfate was evident at the lake bottom in winter, and a smaller decrease in sulfate occurred at snowmelt.

### West Glacier Lake

West Glacier Lake became mixed after snowmelt began and ice cover was gone. There also appeared to be some mixing in May, likely due to water flow under the ice. Nitrates and phosphates were considerably higher in WGL than in EGL. Considerably more anions are delivered to WGL in snowmelt. Nevertheless, nitrate and sulfate levels were relatively low, and were below detection limits in summer, indicating that anions delivered to WGL were utilized and the lake was below saturation for acid anions. The winter peak is an indication of stratification while the snowmelt peak is an indication of input from deposition. Chloride levels peaked during

snowmelt, and gradually decreased throughout the season. As with EGL, sulfate was the major acid anion in WGL. Stratification was evident for sulfate during winter and at peak snowmelt (June). Highest sulfate concentrations occurred at initial snowmelt (May), with a dilution occurring as snowmelt progressed.

Acidity increased slightly during snowmelt, and acidity increased below the secchi depth during winter. The pH by season and depth ranged from about pH 6.0 to 6.8. The highest acidity was at the lake bottom (8.5 m) in early winter. Alkalinity and conductivity remained rather constant throughout the year, but alkalinity peaked at nearly 200 µeq/l near the lake bottom in winter. Alkalinity remained at about 50-80 throughout the profile the rest of the year. There was an increase in conductivity at the lake bottom at snowmelt after ice-out, but conductivity remained relatively constant and low throughout the year and throughout the profile.

Concentrations of the base cations Ca, Mg, Na, and K were lowest in summer, and increased slightly under ice in winter, particularly at the lower lake depths. Highest concentrations of these cations occurred at peak snowmelt. Na concentration patterns were similar to the other base cations except concentrations were highest at initial snowmelt, indicating elution of this ion from the snowpack earlier in the melt season. A slight decrease in cation concentration was evident at initial snowmelt. The initial input of cold meltwater under the ice may have caused mixing of the profile which would result in a dilution of the initial input water.

### Integrated Sample Analysis

Analysis of integrated water samples indicates that samples from specific individual depths may not be representative of the overall lake chemistry (table 2). Means for integrated samples were consistently out of the range of those for individual depth samples. One explanation for the difference might be with the different portions of the water column collected in the two samples. Water from only a small layer of the lake water column is sampled at the individual depths. Thus, a large portion of the lake profile is not sampled with this sampling protocol. Although the integrated sample might provide a sample more representative of the complete lake column, the specific depth chemistry data are essential to explain biological changes noted from plankton samples collected concurrently

from the same depths in these alpine lakes.

WGL hydrology suggests that water flow from catchments into the lake is more confined to defined stream beds than is flow into EGL (Musselman 1994), allowing less soil/water interaction. Soils in WGL watershed are shallower and less developed, and a large percentage of the watershed is exposed quartzite bedrock. There is also a considerable amount of flow directly from the permanent snowfield. There is little opportunity for ion exchange with the watershed. Much of the flow into EGL is from overland flow rather than confined to stream channels at snowmelt, and flow ceases when snowmelt is complete. As a result, nitrate and phosphate levels are considerably higher in WGL than EGL.

### Conclusions

EGL and WGL have differing flow patterns, water chemistry, watershed size, and turnover rates. However, both lakes show similar temporal and spatial patterns of change in water chemistry. Both lakes stratify in winter under ice, and show similar types of changes in water chemistry with lake depth and time of season.

The data indicate that caution must be exercised when sampling high elevation alpine lakes such as these. A sample taken when the lakes are stratified may not be representative of lake water chemistry. Stratification can not be verified when sampling from a single depth. In addition, any sample taken at the lake surface

or any other specific depth may not be representative of an integrated water sample taken throughout the lake profile. Such samples should represent only that specific depth when describing lake chemistry. This difference can occur even for small lakes that might appear to be well mixed in late summer or early fall.

### Literature Cited

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Table 2.—Comparison of integrated lake samples and mean of all specific depth samples for East Glacier Lake and West Glacier Lake by date of sampling.

East Glacier Lake separate-depth sample and integrated sample water chemistry analysis 95% confidence intervals for integrated samples, with means of single/subsample data.

Date	Mean Sep pH	Mean Int pH	SD Int pH	Mean Sep Cond	Mean Int Cond	SD Int Cond	Mean Sep Ca	Mean Int Ca	SD Int Ca	Mean Sep Mg	Mean Int Mg	SD Int Mg
01/13/93	6.68	—	—	10.93	—	—	1.46	—	—	0.40	—	—
02/18/93	6.67	6.56	0.03	11.99	12.37	0.14	1.45	1.33	0.02	0.40	0.36	0.00
04/08/93	—	—	—	11.95	11.75	0.05	1.62	1.46	0.01	0.40	0.35	0.00
05/06/93	6.57	6.42	0.03	12.60	19.30	0.13	1.61	2.33	0.05	0.39	0.58	0.02
06/30/93	6.45	6.36	0.10	7.09	7.12	0.06	0.88	0.97	0.04	0.22	0.24	0.00
07/21/93	6.48	6.43	0.02	6.99	7.33	0.02	0.89	0.88	0.10	0.21	0.20	0.01
08/25/93	6.59	6.62	0.01	6.36	6.42	0.11	0.92	0.95	0.16	0.22	0.23	0.02
09/22/93	6.71	6.72	0.02	6.51	6.27	0.04	0.80	1.80	1.73	0.21	0.23	0.06
12/08/93	6.63	6.73	0.02	8.50	8.32	0.11	1.00	0.99	0.02	0.25	0.25	0.01
Date	Mean Sep Na	Mean Int Na	SD Int Na	Mean Sep K	Mean Int K	SD Int K	Mean Sep NH <sub>4</sub>	Mean Int NH <sub>4</sub>	SD Int NH <sub>4</sub>	Mean Sep Cl	Mean Int Cl	SD Int Cl
01/13/93	0.38	—	—	0.20	—	—	0.02	—	—	0.18	—	—
02/18/93	0.39	0.29	0.01	0.19	0.20	0.00	0.02	0.00	0.01	0.19	0.18	0.01
04/08/93	0.39	0.34	0.00	0.22	0.20	0.01	0.01	0.00	0.00	0.18	0.16	0.00
05/06/93	0.39	0.44	0.01	0.16	0.25	0.01	0.03	0.49	0.04	0.20	0.24	0.01
06/30/93	0.22	0.21	0.00	0.10	0.11	0.01	0.05	0.03	0.05	0.08	0.08	0.00
07/21/93	0.35	0.36	0.02	0.09	0.11	0.00	0.00	0.00	0.00	0.09	0.10	0.01
08/25/93	0.23	0.22	0.00	0.05	0.05	0.01	0.00	0.00	0.00	0.04	0.04	0.00
09/22/93	0.22	0.23	0.01	0.03	0.02	0.01	0.00	0.00	0.01	0.02	0.02	0.00
12/08/93	0.29	0.29	0.00	0.04	0.04	0.00	0.01	0.02	0.02	0.02	0.02	0.00
Date	Mean Sep SO <sub>4</sub>	Mean Int SO <sub>4</sub>	SD Int SO <sub>4</sub>	Mean Sep ANC	Mean Int ANC	SD Int ANC	Mean Sep SiO <sub>2</sub>	Mean Int SiO <sub>2</sub>	SD Int SiO <sub>2</sub>	Mean Sep Al	Mean Int Al	SD Int Al
01/13/93	1.15	—	—	78.49	—	—	1.36	—	—	6.67	—	—
02/18/93	1.23	1.07	0.01	83.19	102.20	0.75	1.58	1.16	0.01	3.60	0.64	0.58
04/08/93	1.14	1.15	0.01	—	—	—	1.14	1.19	0.09	3.65	1.92	0.14
05/06/93	1.07	1.00	0.03	103.60	182.27	0.45	1.53	1.32	—	7.31	11.04	—
06/30/93	0.78	0.74	0.00	46.67	47.13	0.25	—	1.51	0.03	—	14.31	1.76
07/21/93	0.87	0.93	0.00	46.11	48.63	0.45	—	1.46	0.06	—	12.38	0.42
08/25/93	0.74	0.75	0.00	48.14	48.67	0.42	1.13	1.09	0.03	9.84	14.82	7.04
09/22/93	0.81	0.81	0.00	48.93	48.80	0.17	—	—	—	—	—	—
12/08/93	0.94	0.94	0.01	62.67	62.53	0.70	—	—	—	—	—	—

(Continued)

Table 2.—(Continued).

West Glacier Lake separate-depth sample and integrated sample water chemistry analysis 95% confidence intervals for integrated samples, with means of single/subsample data.

Date	Mean Sep pH	Mean Int pH	SD Int pH	Mean Sep Cond	Mean Int Cond	SD Int Cond	Mean Sep Ca	Mean Int Ca	SD Int Ca	Mean Sep Mg	Mean Int Mg	SD Int Mg
01/13/93	6.72	—	—	8.49	—	—	1.04	—	—	0.32	—	—
02/18/93	6.48	6.61	0.02	9.92	9.60	0.03	1.31	1.27	0.05	0.39	0.39	0.01
04/08/93	—	—	—	11.66	10.91	0.02	1.45	1.36	0.04	0.43	0.40	0.01
05/06/93	6.52	6.61	0.04	10.90	10.96	0.03	1.44	1.56	0.02	0.40	0.41	0.00
06/30/93	6.41	6.36	0.02	12.19	12.28	0.15	1.44	—	—	0.40	—	—
07/21/93	6.61	6.73	0.04	6.39	6.49	0.35	0.82	0.77	0.08	0.20	0.20	0.02
08/25/93	6.53	6.57	0.03	5.37	5.41	0.04	0.73	0.80	0.04	0.17	0.18	0.00
09/22/93	6.67	6.67	0.04	5.44	5.46	0.04	0.72	0.79	0.10	0.19	0.20	0.01
12/08/93	6.41	6.35	0.04	8.23	7.87	0.16	0.92	0.90	0.03	0.25	0.24	0.00
Date	Mean Sep Na	Mean Int Na	SD Int Na	Mean Sep K	Mean Int K	SD Int K	Mean Sep NH <sub>4</sub>	Mean Int NH <sub>4</sub>	SD Int NH <sub>4</sub>	Mean Sep Cl	Mean Int Cl	SD Int Cl
01/13/93	0.25	—	—	0.11	—	—	0.04	—	—	0.08	—	—
02/18/93	0.27	0.28	0.00	0.15	0.14	0.01	0.10	0.05	0.00	0.09	0.09	0.00
04/08/93	0.25	0.27	0.01	0.18	0.17	0.00	0.16	0.09	0.01	0.11	0.10	0.01
05/06/93	0.36	0.38	0.02	0.17	0.16	0.02	0.11	0.46	0.27	0.12	0.13	0.01
06/30/93	0.25	—	—	0.22	—	—	0.30	—	—	0.11	0.13	0.01
07/21/93	0.27	0.28	0.01	0.12	0.13	0.04	0.00	0.00	0.01	0.08	0.08	0.00
08/25/93	0.15	0.16	0.00	0.06	0.06	0.00	0.00	0.00	0.00	0.05	0.05	0.00
09/22/93	0.19	0.18	0.00	0.06	0.07	0.01	0.01	0.00	0.00	0.06	0.05	0.00
12/08/93	0.27	0.27	0.00	0.12	0.12	0.00	0.07	0.03	0.01	0.07	0.07	0.00
Date	Mean Sep SO <sub>4</sub>	Mean Int SO <sub>4</sub>	SD Int SO <sub>4</sub>	Mean Sep ANC	Mean Int ANC	SD Int ANC	Mean Sep SiO <sub>2</sub>	Mean Int SiO <sub>2</sub>	SD Int SiO <sub>2</sub>	Mean Sep Al	Mean Int Al	SD Int Al
01/13/93	0.91	—	—	61.80	—	—	0.62	—	—	5.46	—	—
02/18/93	0.83	0.95	0.01	81.79	71.03	0.25	1.11	0.84	0.03	6.51	9.48	0.66
04/08/93	0.76	0.88	0.00	—	—	—	1.28	1.12	0.08	8.24	6.35	—
05/06/93	1.30	1.33	0.01	77.94	79.00	0.44	1.74	1.05	0.00	7.50	6.40	—
06/30/93	0.66	0.47	0.18	102.15	168.73	53.34	0.00	2.59	0.56	—	37.60	32.81
07/21/93	0.84	0.85	0.06	44.69	47.37	1.63	0.00	1.41	0.01	—	11.41	1.97
08/25/93	0.63	0.63	0.00	25.94	26.37	0.78	0.29	0.31	0.02	7.90	7.94	0.99
09/22/93	0.73	0.72	0.00	39.84	40.30	0.56	—	—	—	—	—	—
12/08/93	0.89	0.87	0.00	64.06	59.87	1.31	—	—	—	—	—	—

"Mean Sep" = Mean of the separate depths sample data.

"Mean Int" = Mean of the integrated sample data.

"SD Int" = Standard deviation of the integrated sample data.

"—" = No data.

# Testing the Effectiveness of Shelterbelts in Adapting Great Plains Crop Production to Climate Change: A Simulation Model<sup>1</sup>

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Linear forested systems, especially those deliberately managed as shelterbelts, may help adapt cropping systems in semi-arid grasslands such as the North American Great Plains to climate change. Trees have become increasingly important features in the Great Plains. In this study, the microclimatic effects of shelterbelts gleaned from the literature are inserted into the EPIC crop model to simulate the response of crops to shelter on two hypothetical farms in Nebraska (dryland maize at Mead and irrigated maize at Grand Island). This modified version of EPIC and a version simulating an unsheltered control were subjected to systematic increments to temperature, and increments/decrements to precipitation and windiness in order to examine differences in crop productivity be-

tween the two versions under climate changes. The model results were examined graphically and statistically. The results suggest that shelter boosts dryland maize yields above corresponding unsheltered yields for all levels of climate change. The positive effect of shelter on dryland maize at all levels of temperature increase is greatest for the most severe changes: maximum precipitation deficiency and greatest increase in wind-speed. Precipitation change appears to be the major determinant of differences between shelter and nonshelter dryland maize yields. The story is different for irrigated maize. The differences between shelter and nonshelter yields are small and vary little over escalating degrees of climate change. Under irrigation, temperature change is the main driver of differences between sheltered yields and the open field baseline yields. Despite methodological limitations, the findings suggest that shelterbelts may afford important protection from climate warming.

<sup>1</sup>Poster paper presented at the Interior West Global Change Workshop, April 25-27, 1995, Fort Collins, CO.

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# Predicting the Potential Sensitivity of High Elevation Wilderness Vegetation to Changes in Atmospheric Chemistry—A Strategy<sup>1</sup>

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Our wilderness areas are a unique resource which ensures the maintenance of wild areas in our nation. While these areas are in remote locations they are not isolated from our industrial society and impacts associated with global change. Because of long-range atmospheric transport and the increase in regional air pollution sources, these areas may encounter anthropogenic pollutants.

The Clean Air Act of 1990, as amended, charges the Federal Land Manager (FLM) with the affirmative responsibility to protect air-quality-related-values (AQRVs, any wilderness components that can be modified by human-caused air pollution) in Class I areas from adverse air pollution impacts. Class I areas are wildernesses larger than 5000 acres (including later expansions) which existed as of 8/7/77. This protection is available through implementation of the Act's Prevention of Significant Deterioration (PSD) provisions.

<sup>1</sup>Poster paper presented at the Interior West Global Change Workshop, April 25-27, 1995, Fort Collins, CO.

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**Abstract.**—A new strategy to estimate the sensitivity of alpine plant species to atmospheric deposition is presented. This approach utilizes plant physiological and morphological characteristics to estimate pollutant uptake. The plant characteristics can be determined quickly and easily in the field within the constraints of allowable activities in Class I wilderness areas. Species in two alpine sites have been sampled and the first potential sensitivity rankings of alpine species have been constructed. While the accuracy of these rankings still needs to be verified, they provide a framework for prioritizing species for future research.

This discussion will address the constraints that the PSD process imposes on the scientific process to gather relevant data for the permit evaluation and why conventional air pollutant impact approaches are inadequate to address impacts to vegetation within these constraints. In addition, a new approach to address the protection of remote wilderness plant species will be presented, as well as a summary of the findings from the first field testing of the approach. The focus of this discussion will be on the high elevation, alpine ecosystems which are components of many of the Inter-Mountain and Rocky Mountain Class I wilderness areas. These areas have some unique problems associated with estimating the sensitivity of the vegetation to atmospheric deposition.

## Constraints Imposed by the PSD Permit Process

The PSD program is a preconstruction review and permitting process for major new or expanding sources of pollution. Any major facility seeking a new source permit for location or expansion in a clean air area must

meet several requirements, as specified in the Clean Air Act. It is the responsibility of the FLM to determine whether a proposed source's emissions will have an adverse impact on Class I area AQRVs.

The major constraint of the PSD process is the short review period the FLM has to evaluate a permit application. The review period may be, at most, one field season. Therefore it would be prudent if some monitoring is done before a permit evaluation situation arises since the burden of proof as to the likelihood of impacts is on the FLM.

Many national forests have developed monitoring plans (Air Resource Management Plans) to gather baseline data for their lands and to attempt to detect any current impacts to AQRVs. While surface water chemistry and visibility are currently being monitored in some Class I areas of the Inter-Mountain and Rocky Mountain regions, no monitoring for sensitivity to or impacts on vegetation by pollutants is currently underway because of the lack of methodology and predictive tools. Therefore, permits are currently reviewed on the basis of potential impacts to surface water

chemistry and visibility and plant sensitivity is not considered. This may adequately protect wilderness ecosystems from effects caused by nitrogen and sulfur deposition, but will not adequately protect the ecosystem from impact by chemicals, such as ozone, where the primary impact is expressed by plants.

The PSD process establishes no prioritization for the importance of different components of the ecosystem. Each wilderness is a unique compilation of biotic and physical factors which interact to form the ecosystem. Therefore to develop a procedure to estimate the sensitive component of any wilderness ecosystem, the approach must be flexible. It must be applicable to each unique permit application scenario, taking into account the specific wilderness area that may be impacted with its specific diversity of species, genotypes, pollutant chemicals, and physical conditions. Therefore, the optimal approach would be one which incorporates data collected from the wilderness area in question with the model estimates of pollutant transport and exposure.

The data to be collected in each wilderness area must be simple and compatible within the constraints imposed by the Wilderness Act of 1964 (i.e. requiring no motorized transportation or excessive destructive sampling). This is complicated by the non-uniformity and complexity of the alpine landscape. The alpine environment is characterized by the severe physical environment of high radiation, winds, and snow fall. The interaction of these factors with the topography creates a mosaic of microenviron-

ments across the alpine landscape. The most obvious feature of this mosaic is the alternating pattern of windblown, snow-free sites with deep snow-accumulation areas. Distinct vegetative communities have evolved in response to these different snow regimes (Komarkova and Webber 1978).

The same mosaic of snow regimes that cause differences in plant community structure also creates a mosaic across the alpine landscape in the potential deposition rates of anthropogenic pollutants. It has been shown that distinct areas of the alpine tend to accumulate the deposition of fallout from nuclear testing (Hutchison-Benson et al. 1985). It is clear that for a given polluted air mass over an alpine environment, the pollutant loading to the ground will be non-uniform. In light of the potential for such heterogeneous pollutant loading rates, the pursuit of the most sensitive component of the ecosystem is inappropriate if it is only defined as the component with the lowest threshold of tolerance to a pollutant. More appropriately, the approach must be to identify the first component of the ecosystem which will exhibit a measurable change in response to deposition from a given air mass. This involves the identification of 1) the relative pollutant loading rates to the mosaic of alpine microenvironments and 2) the sensitivity of each community and its individuals to the pollutants delivered to its location. The combination of these two characteristics will provide a means of identifying which component of the system is most likely to show effects first in a given atmospheric chemistry.

## Comparison of the Problem to Other Air Pollution Effects Programs

It is clear that the responsibility of determining the alpine species most likely to be affected once exposed to a polluted air mass is no small task - we are dealing with incredible diversity in a harsh environment. This alone makes this situation different than past air pollution-effects programs such as the National Acid Precipitation Assessment Program (NAPAP) and National Crop Loss Assessment Network (NCLAN). The NCLAN program was established to provide information on the economic impacts of ozone and sulfur dioxide on selected crop species. The NAPAP program was established to gain information to attempt to explain or unravel the components of the apparent 'forest decline' in the U.S. The species to be studied under each of these plans were specified because of the nature of the programs. Under the PSD program, there are no means of prioritizing the wilderness plant communities or species. The congressional mandate specifically implies that all the organisms in wilderness are of equal importance with respect to their protection. The PSD program is also different from the other programs because of the fact that it is designed to prevent damage from occurring - not to assess damage that is already occurring. Currently, there are no field observations of impacts in alpine wildernesses to help construct a preliminary list of sensitive alpine species.

Because of the differences between the PSD program and

past programs it is not surprising that the standard approach (dose-response studies) implemented in the past programs are not applicable here. The most obvious problem with the conventional approach is the fact that the sensitivity of an extraordinary number of species must be assessed. It is not feasible to construct an exposure-impact relationship for each and every species found in all alpine wilderness areas of the USA.

Additionally, there is a unique problem with conducting dose-response studies in controlled environments with alpine plants. The growth form of many alpine plants is a consequence of the harsh environment in which they live. It is not possible to transport alpine plants out of their environment without altering their morphology and quite likely their physiology and pollutant sensitivity. The expense and time required to attempt to simulate the alpine environment adequately is unacceptable within the criteria of this situation. There is always a question about the validity of the extrapolation of controlled environment data to the field, because of interactions of the pollutant effects with environmental factors. The severe environmental conditions present in high elevation areas may interact with the sensitivity of the species to pollutant impacts, further complicating the interpretation and extrapolation of data from experiments conducted under less severe conditions.

Conducting dose-response experiments in the alpine environment, outside of a wilderness area because of the obvious conflict between this activity and

the provisions of the Wilderness Act, is prohibitive because of the remoteness of alpine areas (i.e. the cost of installing line power and preventing damage to the fumigation system by the elements). Because of the slow growing nature of alpine plants, at least several seasons of exposure would be required before an effect would be measurable and could be attributed to the pollutant. This approach should be explored, yet, because of the technological advances that it requires, it is unlikely to provide information to the FLM in the near future. In addition, this approach is static such that the sensitivity determined by this technique would only apply to the conditions that existed during the study, and may not be applicable under different conditions that may be present under a changing climate.

### The Strategy

What are our alternatives? Because of the magnitude of the problem, it is unlikely that the actual sensitivity of wilderness plant species will ever be known. We have to develop a way to estimate sensitivity from easily measured parameters. This requires information on the mechanisms of atmospheric pollutant effects which could be incorporated into a model. We know that there are 3 components of sensitivity to direct impacts of atmospheric chemistry to plants: exposure, plant uptake or dose, and biochemical sensitivity of the plant cell (table 1).

The first component, pollutant exposure, is one that is modeled

and estimated from air pollution transport models. The current models predict possible air chemistries above a given land area and do not predict deposition rates to different microenvironments. It is particularly difficult to make accurate predictions of potential atmospheric chemistries in mountainous terrain. Using these data alone to predict pollutant impacts on vegetation is unreliable. The relationship between exposure and impacts is quite variable from species to species (Reich 1987).

If the second component is added, plant uptake, another level of resolution is added to the prediction of potential impacts. Plant uptake can be divided into two categories, uptake of gaseous pollutants and uptake of water-deposited pollutants. Aerodynamic and stomatal conductance of plant leaves influence gaseous pollutant uptake; and leaf wettability and crown architecture influence interception and assimilation of pollutants delivered in precipitation. The relationships between pollutant uptake and these parameters have been established over several plant species (Mansfield and Freer-Smith 1981, Boyce et al. 1991). With measurements of stomatal and leaf characteristics of alpine plants and estimates of ambient pollutant concentrations and durations from the air transport models it is possible to estimate pollutant uptake by alpine plants.

Measurements of leaf conductance can easily and quickly be made with a steady-state porometer. This instrument is fully field-portable and can be carried and operated by a single person. Measurements on a leaf can

Table 1.—The components of plant sensitivity to atmospheric pollution. Examination of the mechanisms by which air pollutants affect plants has revealed that impact is more closely related to pollutant uptake than exposure.

Components of sensitivity:

- 1. Dose - how much gets into the plant
    - a. exposure (concentration in the air)
    - b. plant uptake ability - is a function of:
      - leaf conductance - uptake of gases (O<sub>3</sub>, SO<sub>2</sub>, NO<sub>2</sub>)
      - leaf surface and crown structure - foliar absorption of wet deposition
      - nutritional status - uptake from the soil
  - 2. Internal Reactions - pollutant interaction in the cell
- Progress is being made in this area, but currently there are no consistent correlations between biochemical characteristics of cells and their sensitivity to damage among species.

Table 2.—Estimates of the most sensitive species (of the 24 species surveyed) to the uptake of gaseous pollutants, based on leaf conductance at two alpine sites (Monson 1989).

GLEES	Niwot Ridge
<i>Bistorta bistortoides</i>	<i>Acomastylis rossii</i>
<i>Penstemon whippleanus</i>	<i>Bistorta bistortoides</i>
<i>Psychrophila leptosepala</i>	<i>Carex scopulorum</i>
<i>Calamagrostis purpurascens</i>	<i>Psychrophila leptosepala</i>
<i>Erigeron peregrinus</i>	<i>Hymenoxys grandiflora</i>

Table 3.—Estimates of the most sensitive species (of the 27 species surveyed) to the uptake of pollutants from wet deposition, based on leaf, flower, and crown characteristics (Monson 1989).

Flower wettability	Leaf and crown water retention
<i>Psychrophila leptosepala</i>	<i>Clementsia rhodantha</i>
<i>Erythronium grandiflorum</i>	<i>Potentilla diversifolia</i>
<i>Phlox pulvinata</i>	<i>Erigeron melanocephalus</i>
<i>Achillea lanulosa</i>	<i>Hymenoxys grandiflora</i>
<i>Potentilla diversifolia</i>	<i>Potentilla nivea</i>

typically be accomplished in 15 to 30 seconds. In a survey of 24 alpine species in two alpine sites along the east side of the Rocky Mountains (Niwot Ridge, Nederland, CO and Glacier Lakes Ecosystem Experiments Site (GLEES), Snowy Range, WY), a wide range in stomatal conductance was detected suggesting a range of potential sensitivity to

the uptake of gaseous air pollutants (table 2). In a survey of 27 alpine species at GLEES, the crown retention of precipitation can be accurately predicted on the basis of some simple measurements such as crown height, diameter and width of the leaves at the base of the petiole (Monson et al. 1992).

Thus, by conducting a few selected measurements of these traits for alpine species, one can make some predictions about which species would be most susceptible to the uptake of gaseous and water-deposited pollutants (table 2, table 3). Making the measurements in each threatened wilderness area would further improve our predictive ability by avoiding extrapolations across genotypes and site characteristics, which have been shown to affect these measurements (table 2). By quantifying the proportion of a given community that is composed of a sensitive species, one can develop an index of overall community susceptibility to pollutant uptake. Finally, by quantifying the proportion of a given community (with their characteristic sensitivities) within a regional flora, an index can be developed to estimate the potential floristic susceptibility of a landscape to pollutant uptake.

At present, the empirically-based approach of estimating pollutant uptake rates, as described here, is most feasible for rapidly assessing the potential sensitivity of individual alpine wilderness areas to certain anthropogenic pollutants. Estimates of plant sensitivity to pollutants would have greater accuracy if more information on the internal sensitivity of plants to assimilated pollutants was known. There is relatively little information available on factors that control this aspect of sensitivity in plants. At this time, the relationships between biochemical characteristics and sensitivity are not well enough understood among species to incorporate this level of

detail into any wilderness vegetation monitoring program.

Before the current sensitivity rankings of alpine species (Monson 1989) can be used in the PSD review process, verification of the approach must be done with a subset of alpine species. This strategy assumes that the relationships between pollutant uptake and impacts that have been found for agronomic and tree species applies to wild alpine species; the relationships should be confirmed for alpine species. Comparisons of leaf conductance and impacts has begun in controlled fumigations in greenhouses using seedlings grown from seed collected from two alpine species (Berrang, personal communication). While these tests have all the problems discussed above regarding controlled-environment studies, they will provide a first approximation. Field verification of the approach is also being considered.

## Summary

By relying on the exposure-impact relationship established with other plant species, predictions of potential impact at a very coarse level to alpine species can be made using exposure data generated by meteorological models. This is, however, not sufficient to ensure that the FLM is, in fact, protecting the area from impacts because of the poor correlation between exposure and impacts among plant species (Reich and Amundson 1985). The addition of information on the uptake of pollutants by plants can substantially improve our prediction because of the better relation-

ship between uptake and impact (Reich 1987). Estimates of pollutant uptake ability can be gathered in one field season by measuring stomatal conductance and leaf and crown characteristics.

This approach is progressive. This scheme is sufficiently flexible such that improvements can be made over time. The relationships can be adapted as more research information becomes available and can progressively be made more specific for alpine plants. Each step of this approach can be improved by improved understanding of air pollution delivery and impacts in general and our understanding of high elevation plants and their responses to pollutants. In this way the FLM's ability to evaluate PSD permits will evolve with the entire air pollution effects research effort, and not be limited to benefiting only from those studies that directly apply to alpine plant sensitivity.

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# Ozone and Carbon Dioxide Fluxes in a Subalpine Spruce-fir Forest Ecosystem<sup>1</sup>

Karl Zeller<sup>2</sup>

## Introduction

RMFRES RWU 4452 has made several ozone ( $O_3$ ) and carbon dioxide ( $CO_2$ ) trace gas flux measurements in the Snowy Range, WY GLEES research area over the past few years. These measurements were made using the micrometeorological eddy correlation technique at two sites: one 6 m above tree canopy height on the Brooklyn tower (ozone only); and the other below canopy height, 1-2 m above a wet alpine meadow surface near the Brooklyn tower. Diel  $CO_2$  vertical flux cycles change dramatically from expected daytime uptake (downward) and nighttime emissions (upward) during the growing season to predominantly upward during winter above the snow surface. Diel  $O_3$  vertical flux cycles above the tree canopy vary from normal deposition during the summer growing season to upward in the presence of snow cover. Diel  $O_3$  vertical flux cycles above the wet meadow are downward (deposition) as expected year round, however winter-time deposition measured above 1-2 m snow depths are signifi-

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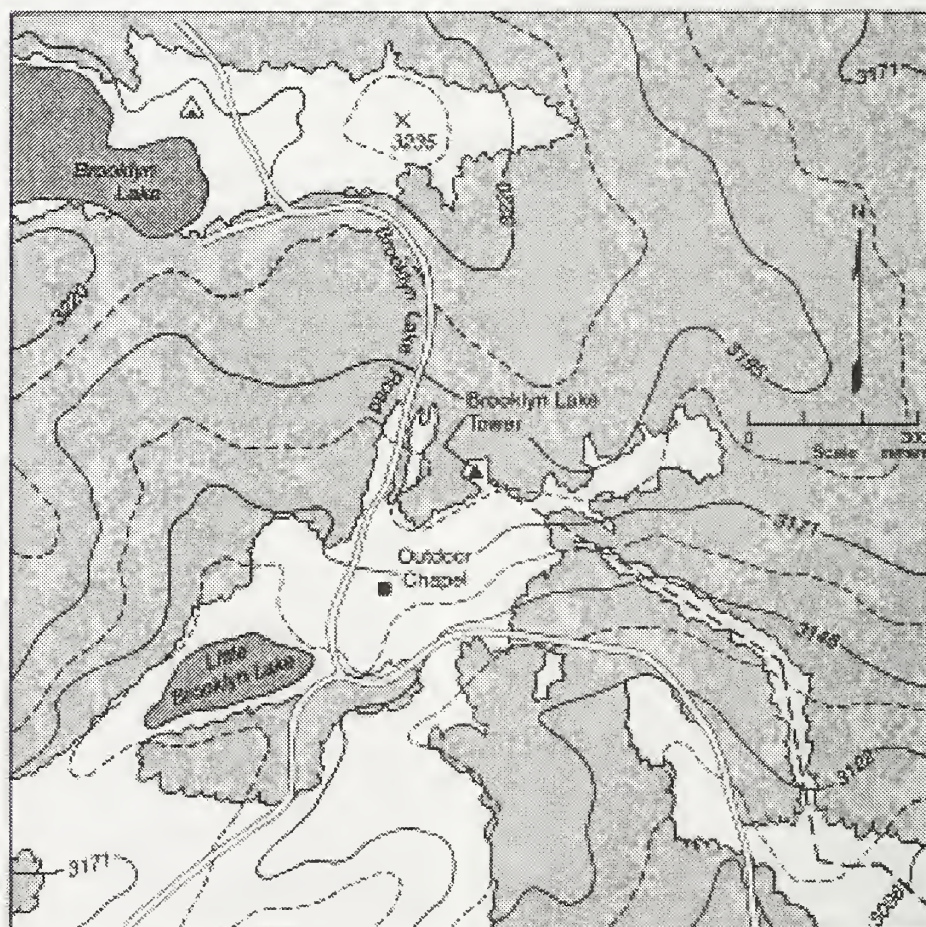
cantly smaller than fluxes measured above snow cover reported in the literature.

## Ozone and Ozone Fluxes

### Above Tree Canopy

Forest ecosystems play a role in the uptake and destruction of tropospheric  $O_3$ . This role and the tropospheric  $O_3$  budget in remote

forested ecosystems is uncertain [Lefohn, 1992]. The known rate of  $O_3$  deposition is rapid during the growing season and slower during winter months [Wesely, 1983]. Ozone deposition is retarded further by surface snow cover [Wesely et al. 1981, Stocker et al. 1995]. Our data show the unexpected effect of snow cover on  $O_3$  fluxes as measured on the Brook-



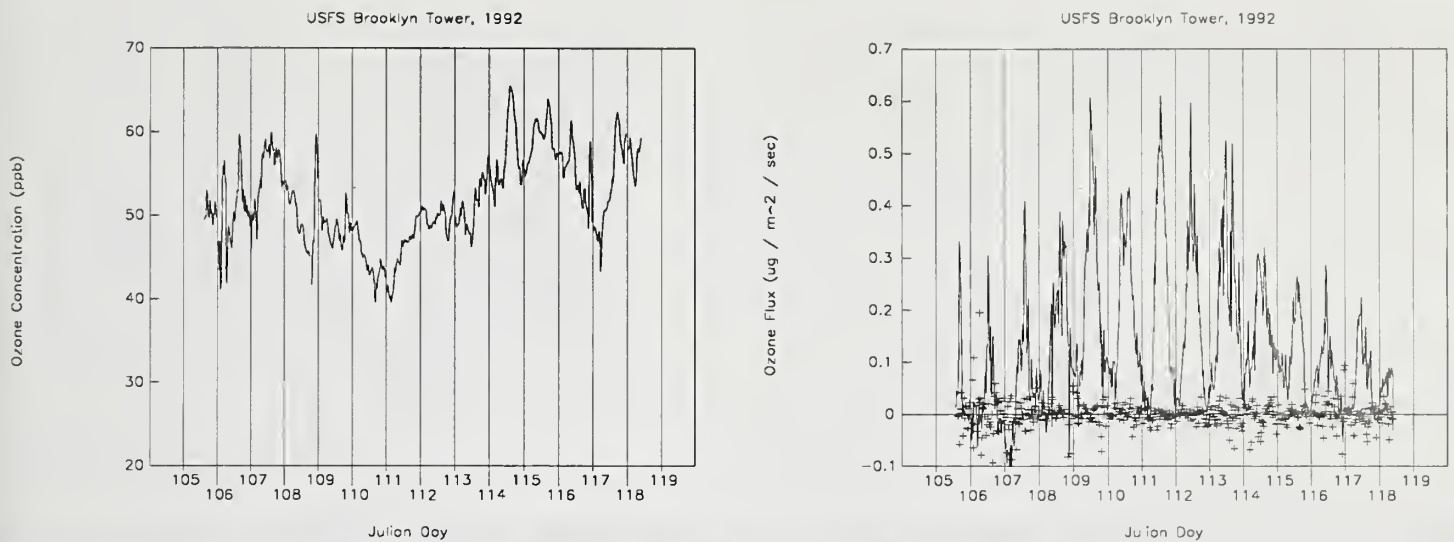


Figure 2.—Ozone concentration and deposition flux for April 14-27, 1992 (Julian day (JD) 106-117).

lyn tower above a subalpine spruce-fir forest (fig. 1.) at the U.S. Forest Service's Glacier Lakes Ecosystem Site (GLEES) [Zeller & Hehn, 1994]. Ozone concentrations at GLEES average from 45 to 60 ppb year round [Musselman et al., 1992; Wooldridge et al., 1994], and are typical of high altitude rural sites [Wunderli and Gehrig, 1990]. However upward fluxes as large as  $0.5 \mu\text{g m}^{-2} \text{s}^{-1}$  were measured during the 1991-92 winter season.

These values, equivalent to  $10.8 \text{ kg km}^{-2} \text{ day}^{-1}$ , are similar to the peak summer 1992 growing season downward fluxes measured at the same location.

Figure 2 shows the day-to-day consistency of the upward  $\text{O}_3$  fluxes for several days. Half-hour average (a)  $\text{O}_3$  concentration in parts per billion (ppb) and (b)  $\text{O}_3$  flux (lines) and vertically integrated time rate of  $\text{O}_3$  change (+) in micrograms per square meter per second ( $\mu\text{g m}^{-2} \text{s}^{-1}$ ) for the

period April 14 to 27, 1992. Temperatures ranged from  $5^\circ\text{C}$  to  $-10^\circ\text{C}$  during this period. Ozone fluxes exceeded  $0.5 \mu\text{g m}^{-2} \text{s}^{-1}$  and deposition velocities ranged from  $-0.8$  to  $0.2 \text{ cm s}^{-1}$

Figure 3 covers the period snowmelt ended and the daytime  $\text{O}_3$  flux direction switched from upward to downward. Ozone fluxes ranged from positive to negative on any day during this period but remain predominately negative after JD 138. Half-hour

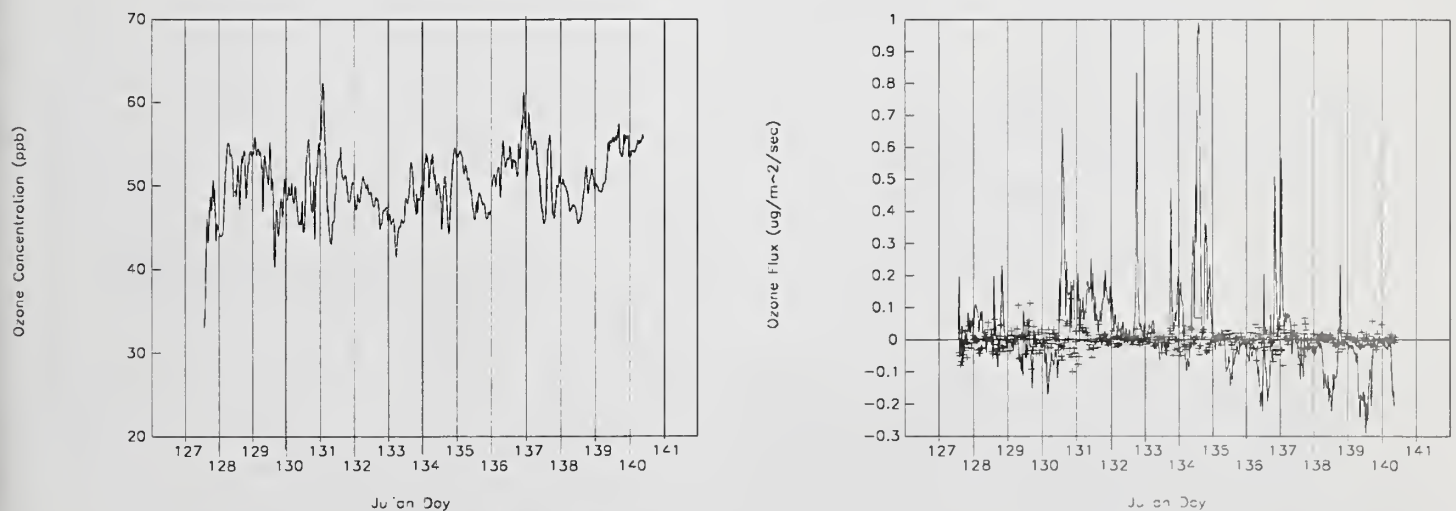


Figure 3.—Ozone concentration and deposition flux for May 6-19, 1992 (JD 127-140).

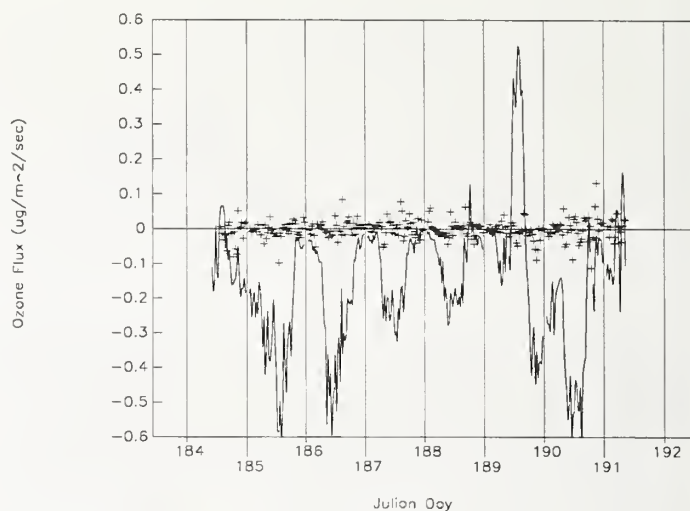
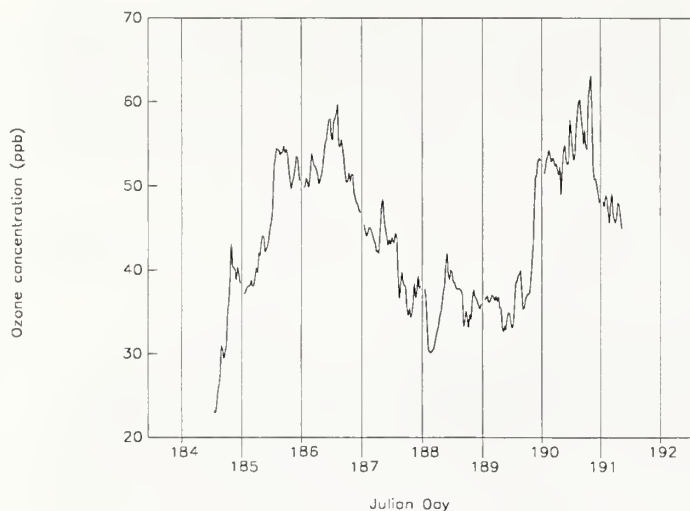


Figure 4.—Ozone concentration and deposition flux for July 2-9, 1992 (JD 184-191).

average (a)  $O_3$  concentration in parts per billion (ppb) and (b)  $O_3$  flux (lines) and vertically integrated time rate of  $O_3$  change (+) in micrograms per square meter per second ( $mg\ m^{-2}\ s^{-1}$ ) for the period May 6 to 19, 1992. Temperatures ranged from  $3^\circ$  to  $10^\circ C$  above zero except for a brief nighttime excursion below freezing on JD 131. Deposition velocities also peaked at  $-1.5\ cm\ s^{-1}$  on JD 131 but generally ranged from  $-0.4$  to  $0.3\ cm\ s^{-1}$ .

Figure 4 shows the typical negative  $O_3$  fluxes that occur during the summer growing season. The downward diurnal flux pattern is briefly interrupted on JD 189 when it rained 0.3 mm. Half-hour average (a)  $O_3$  concentration in parts per billion (ppb) (b) and  $O_3$  flux (lines) and vertically integrated time rate of  $O_3$  change (+) in micrograms per square meter per second ( $mg\ m^{-2}\ s^{-1}$ ) for the period July 2 to July 9, 1992. Temperatures during this period ranged from  $5$  to  $18^\circ C$  but

remained below  $7^\circ C$  on JD 189. Deposition velocities during this period ranged from  $-0.37$  on JD 189 to  $0.4\ cm\ s^{-1}$ .

Figure 5 shows the transition from negative daytime  $O_3$  fluxes to positive fluxes. During this period, temperatures dropped near to below  $0^\circ C$  and RH increased from 30 to 80% at the same time  $O_3$  fluxes turned positive. Although snow depth records were not taken at this time, based on the meteorological data it is most likely that snow

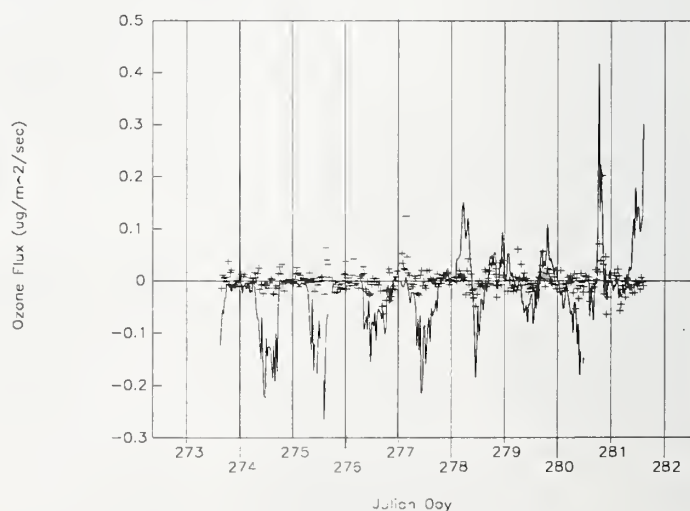
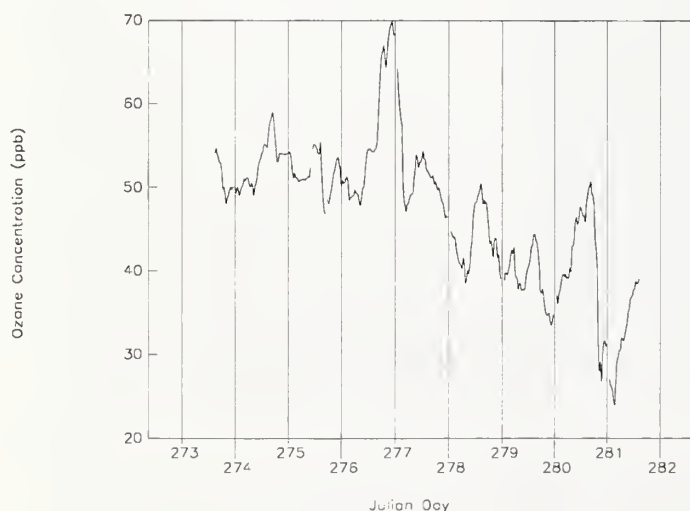


Figure 5.—Ozone concentration and deposition flux for September 29-October 8, 1992 (JD 274-281).

flurries started JD 278 and snow started accumulating on the ground by JD 279. Half-hour average (a)  $O_3$  concentration in parts per billion (ppb) and (b)  $O_3$  flux (lines) and vertically integrated time rate of  $O_3$  change (+) in micrograms per square meter per second ( $mg\ m^{-2}\ s^{-1}$ ) for the period September 30, 1992, to October 7, 1992. Prior to JD 278 daytime temperatures ranged from 7° to 15 °C then dropped to between 0° to 5 °C and finally dipped below freezing on JD 280. Deposition velocities ranged from -0.5 to 0.3  $m\ s^{-1}$  during this period.

## Ozone Below Tree Canopy

Ozone fluxes were measured by eddy correlation below and adjacent to the *Picea engelmannii* (48%), *Abies lasiocarpa* (48%), *Pinus contorta* (4%) canopy at 1-2 m height in an open meadow site in the Snowy Range Mountains of Wyoming during 1994. The measurements were made in April over 2 m deep snow cover, in June at the end of spring melt over saturated soil with very little vegetation and in August over full summertime vegetation. Results show that  $O_3$  flux is consistently downward:  $-0.01 \pm 0.009\ \mu m^{-2}\ s^{-1}$  above the snow-air interface, increasing to  $-0.25 \pm 0.07\ \mu m^{-2}\ s^{-1}$  by the end of spring melt, and  $-0.35 \pm 0.09\ \mu m^{-2}\ s^{-1}$  above the full-growing meadow canopy. Daytime surface  $O_3$  uptake resistance values over snow at this site were between 40 and 80  $s\ cm^{-1}$ , higher than above-snow resistances reported elsewhere. The snow surface in a deep-snow, subalpine environment, provides a minimal sink for  $O_3$ . The 1994 meadow measurements show consistent downward  $O_3$  fluxes that increase dramatically and change diurnal patterns with change in season. Diurnal  $O_3$  concentration patterns also change from winter to summer corresponding to changes in  $O_3$  deposition. The April-May 1994 flux measurements associated with snow cover provide for very large  $O_3$  surface resistances.

In figure 6a, the winter sample period experienced a diurnal concentration variation of about 4 ppb. The average maximum daily values change little by the end of spring melt, however the diurnal variation increased to about 14 ppb because of nighttime decreases in  $O_3$  concentration. This day-night variation increased to about 20 ppb by the August period. Average diurnal changes and standard deviations in (a)  $O_3$  concentration; (b)  $O_3$

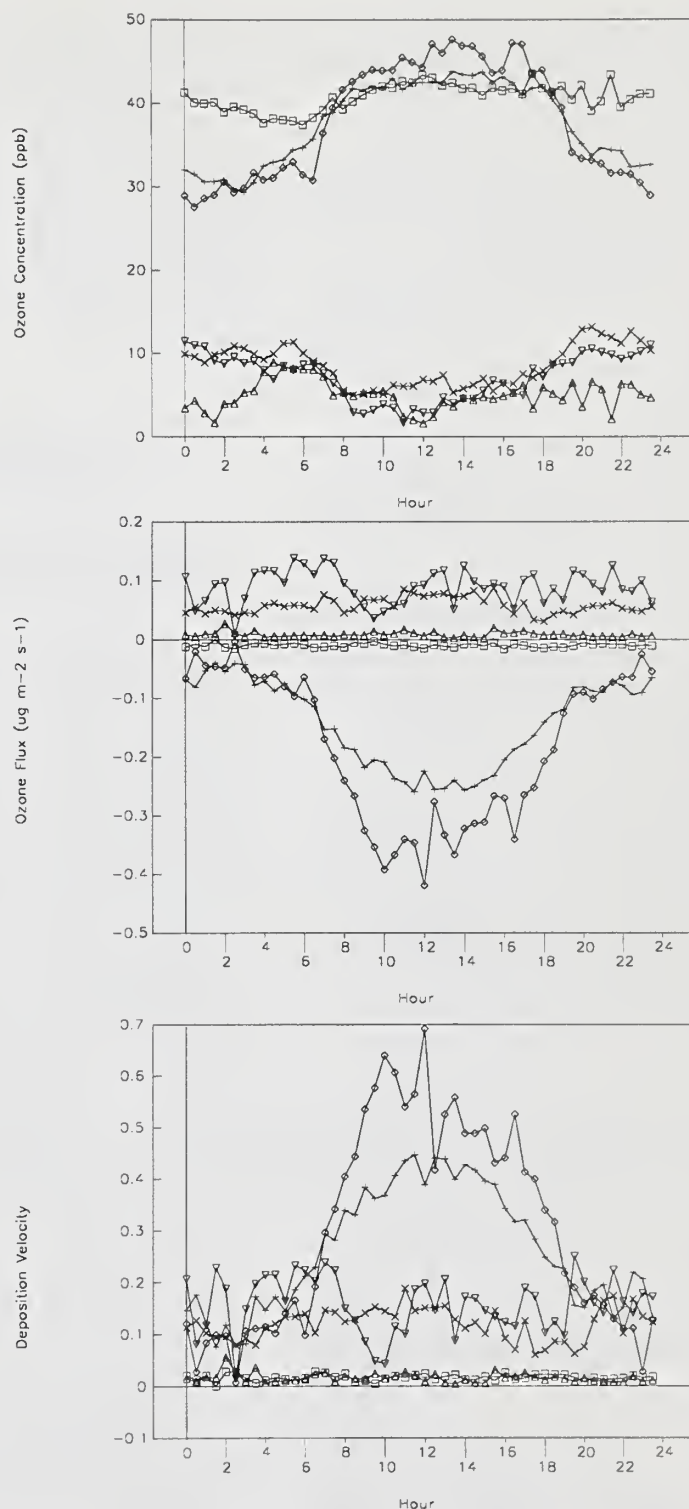


Figure 6.—(a) The diurnal  $O_3$  concentration averages and standard deviations (TECO49 data) for each of the three periods; (b) for each of the three periods, seasonal changes in diurnal ozone flux corresponding to the concentration patterns shown in figure 6.a; (c) the diurnal average  $O_3$  deposition velocities (in  $cm\ s^{-1}$ ) for each of the three periods.

deposition flux; and (c)  $O_3$  deposition velocity for April 24-May 3, 1994 ( $\square$  average,  $\Delta$  standard deviation); June 7-21, 1994 (+ average,  $\times$  standard deviation); and August 2-10, 1994 ( $\diamond$  average,  $\nabla$  standard deviation).

During the April 24-May 3 (fig 6b.), period fluxes averaged about  $-0.01 \pm 0.009 \mu g m^{-2} s^{-1}$  with no diurnal variation. These values are about 35% smaller than fluxes measured over aged snow a few cm depth in a prairie grassland ecosystem 150 km southeast of the GLEES area (Stocker et al., 1995). By the end of snow melt, June 7-21, a well developed diurnal deposition wave emerged with maximum average daytime fluxes of  $-0.25 \pm 0.07 \mu g m^{-2} s^{-1}$ . The meadow during this period was flooded with a few cm of surface runoff water by midday. Vegetation at this time was limited to the previous season's dead compacted grasses, herb, and shrub stems including a few shoots of new growth toward the end of the period. The August 2-10 period shows summertime  $O_3$  fluxes increasing at a faster rate in the morning and achieving greater midday values,  $0.35 \pm 0.09 \mu g m^{-2} s^{-1}$  because of additional  $O_3$  uptake by plant respiration and the added leaf surface area. Deposition can be further parameterized through the simple resistance analogy [eq. 1].

$$V_d = 1 / (r_a + r_c) \quad (1)$$

Here  $r_a$  is atmospheric resistance and  $r_c$  total surface resistance. Daytime  $r_c$  values for  $O_3$  ranged between 40 to 80  $s cm^{-1}$  for the April 24-May 3 period, 2.5-3.5  $s cm^{-1}$  for June 7-21, and 2-3  $s cm^{-1}$  for August 2-10. The winter scenario  $r_c$

values compare to 23  $s cm^{-1}$  over aged snow and 8  $s cm^{-1}$  over new snow report by Stocker et al. (1995) for a grassland ecosystem and 35  $s cm^{-1}$  over a completely snow-blanketed northeastern Illinois field site (Wesely et al., 1981). The snow in the Brooklyn Lake meadow during this period would classify as aged snow.

## Carbon Dioxide and Carbon Dioxide Fluxes

### Carbon Dioxide Below Tree Canopy in Open Meadow

Seasonal ambient eddy correlation carbon dioxide ( $CO_2$ ) flux measurements were made utilizing a sonic anemometer and an in-situ open-path fast response infrared gas  $CO_2$  analyzer. These measurements (fig. 7) were taken at 1-2 m height above the wet sub-alpine meadow (grass canopy). Significant changes in seasonal diurnal  $CO_2$  vertical flux patterns were observed. During the growing season the diurnal cycle of  $CO_2$  fluxes were downward during daylight and upward at night as expected because of photosynthesis and respiration. In winter, 1-2 meters above the snow surface at the same location,  $CO_2$  fluxes were upward during daylight (fig. 8), exactly opposite to the growing season observations, and zero at night. These upward fluxes signify  $CO_2$  emissions with measured values of 0.36  $mol m^{-2} d^{-1}$ . Simultaneous measurements of atmospheric turbulence and  $CO_2$  concentrations show that air turbulence is the primary mechanism for vertical  $CO_2$  transport above the air/snow interface in winter. Night time ambient  $CO_2$  concentrations at 1

meter increased 2 to 3% above background levels when wind speeds are relatively calm indicating that  $CO_2$  is still emitted from the snow but not rapidly dispersing upward. The 1991 winter time  $CO_2$  emission estimates based on measured  $CO_2$  gradients within the snow, diffusion coefficients and an average snow porosity at a snow-covered location, in a forested opening 100 meters east of the  $CO_2$  eddy correlation measurement site, have been calculated and reported to be as high as 0.137  $mol m^{-2} d^{-1}$ , one third the measured  $CO_2$  emissions presented here.

## Conclusions.

### Ozone Above Tree Canopy

The  $O_3$  flux data measured by eddy correlation at the GLEES Brooklyn tower, Snowy Range, Wyoming, show reasonable summer growing season deposition ( $-0.5 mg m^{-2} s^{-1}$ ) and deposition velocity (0.4  $cm s^{-1}$ ). During winter and nongrowing seasons, upward  $O_3$  fluxes were measured. The late winter upward fluxes are the same magnitude as the summer downward fluxes, and  $V_d$ 's frequently approached  $-0.9 cm s^{-1}$ . As  $O_3$  does not readily deposit on snow, the measured rate of  $O_3$  deposition is expected to decrease during the winter but not reverse direction. The flux directional transition is apparently seasonal. The explanation for the upward  $O_3$  fluxes remains unknown but suggest either: (1) some unknown source of  $O_3$  below the 23-meter measurement height; or (2) some other mechanism affecting local  $O_3$  fluxes: three possibilities were presented here.

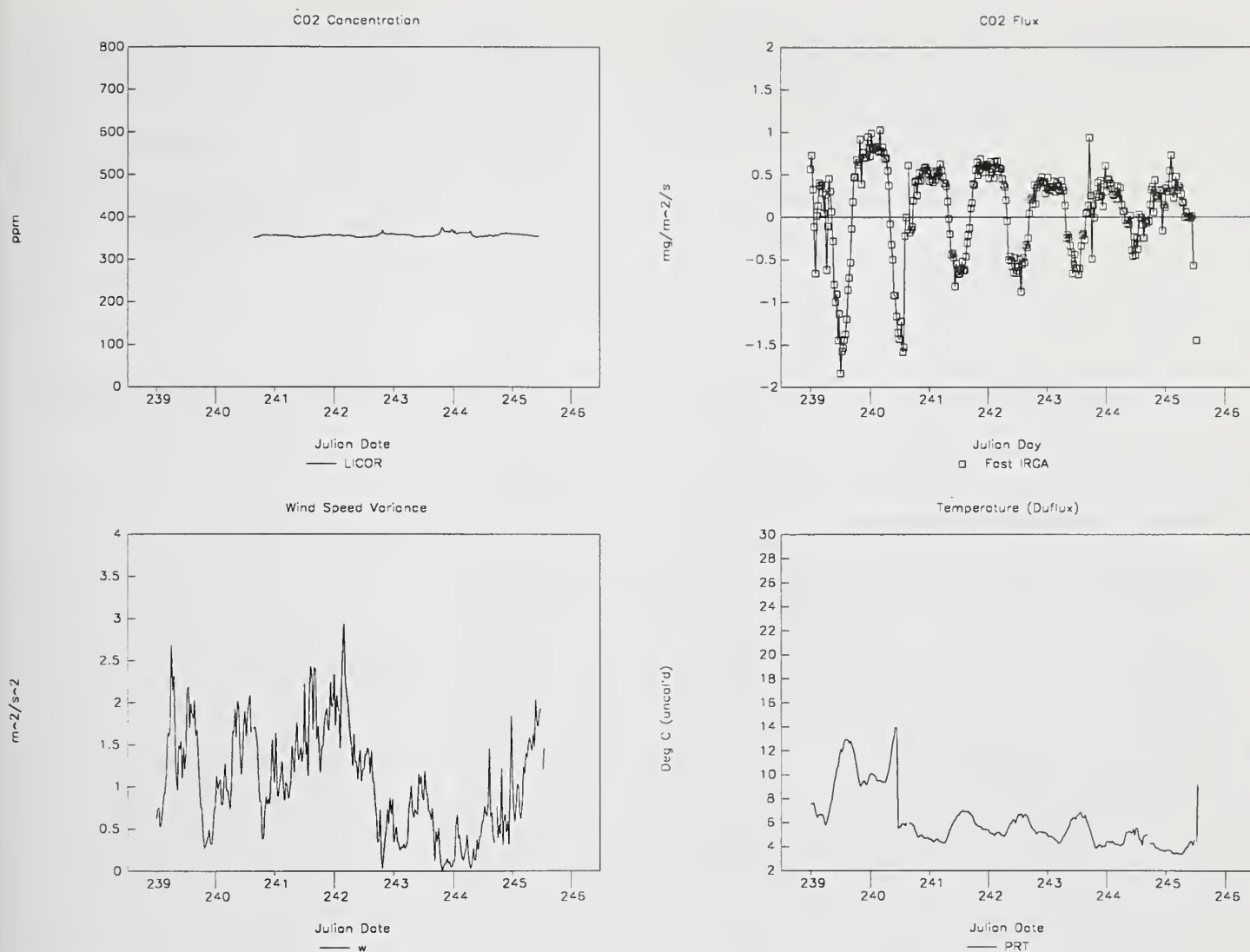


Figure 7.—The average CO<sub>2</sub> concentration, CO<sub>2</sub> flux, vertical wind speed variance, and temperature for a 7-day period in August 1992. Note daily CO<sub>2</sub> cycle appears to respond to the daily temperature and vertical wind variance cycle.

### Ozone Below Tree Canopy in Open Meadow

Ozone deposition to deep snow in a rural subalpine meadow environment is consistently downward but very slow:  $-0.01 \pm 0.009 \text{ m m}^{-2} \text{ s}^{-1}$ . In the absence of both snow and active vegetation, O<sub>3</sub> deposition increases to  $-0.25 \pm 0.07 \text{ m m}^{-2} \text{ s}^{-1}$ . Over an actively growing grass-herb-shrub wet subalpine meadow, average daytime fluxes are  $-0.35 \pm 0.09 \text{ m m}^{-2} \text{ s}^{-1}$ . Daytime surface O<sub>3</sub> uptake resistance over deep snow can be 40 to 80 s cm<sup>-1</sup>, demonstrat-

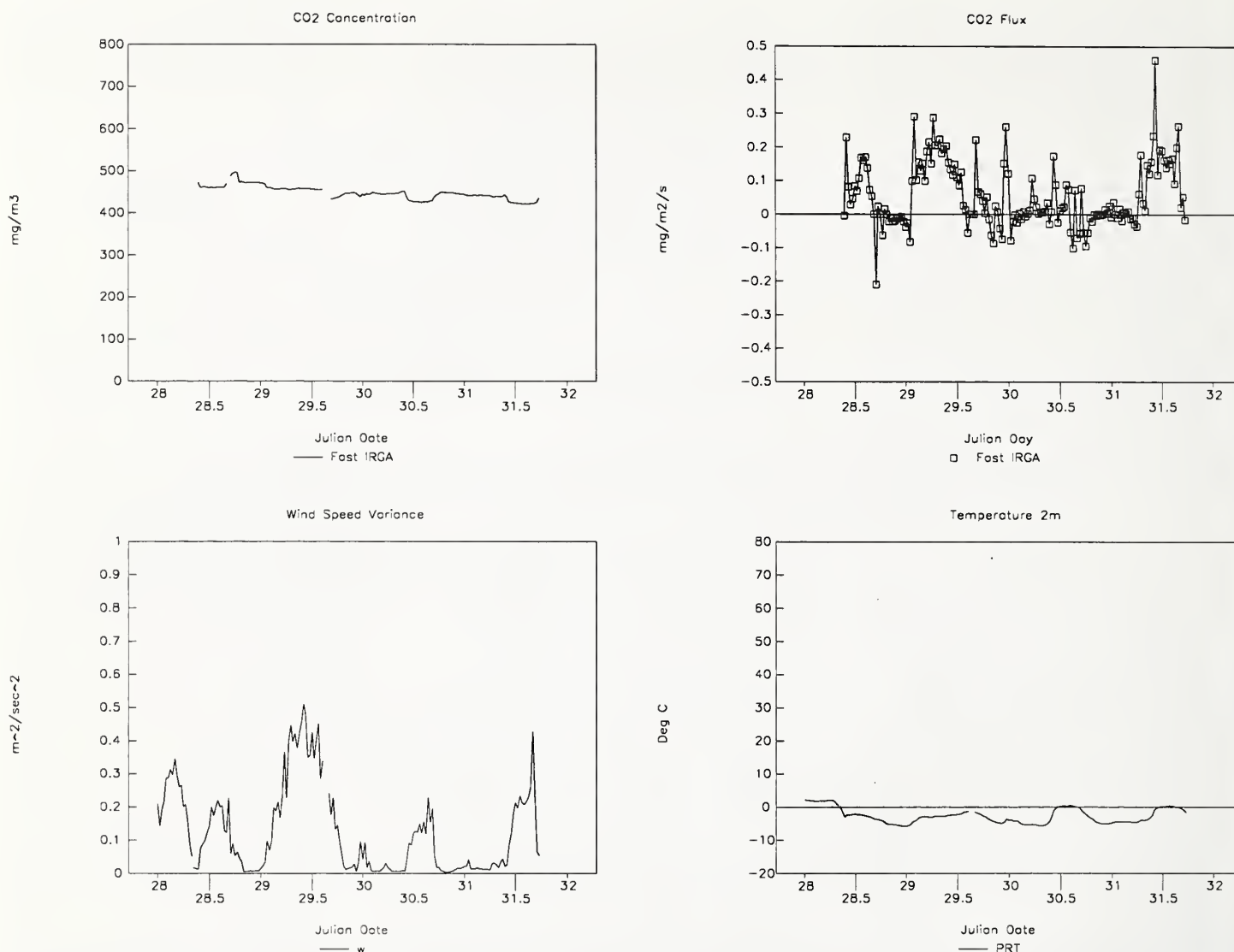
ing that the snow surface in a relatively deep-snow (2 m), subalpine environment, provides a minimal sink for O<sub>3</sub>.

### Carbon Dioxide Below Tree Canopy in Open Meadow

Carbon Dioxide fluxes measured in the Brooklyn wet meadow site demonstrate normal diel cycles during the summer growing season. During the winter, however the meadow site appear to be a net CO<sub>2</sub> producer

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**Figure 8.**—The average CO<sub>2</sub> concentration, CO<sub>2</sub> flux, vertical wind speed variance and temperature during a 4-day period in January 1993. Note daily CO<sub>2</sub> cycle appears to respond to the daily wind variance for this wintertime scenario.

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# The Annual North American Dendroecological Fieldweek: A Workweek in Applied Tree-Ring Research<sup>1</sup>

Peter M. Brown and Paul J. Krusic<sup>2</sup>

## Introduction and Purpose of the Fieldweek

Human history - that which consists of written or instrumental records - often does not adequately cover the range of past variability in many natural processes because of either the short length of available records or gaps in their spatial coverage, or both. Information about past variability is necessary to identify boundary conditions against which to assess future variability, especially to detect unprecedented changes that may be the result of human-induced climate or ecological change. Researchers in many natural science disciplines must therefore turn from instrumental or other written records to proxy data to broaden our understanding of temporal and spatial variability in natural phenomena under study.

Proxy data derived from tree-ring research have proven very

valuable in disciplines such as climatology, ecology, forestry, hydrology, and geology. Trees record many events or processes that influence annual growth patterns. Dendrochronology is concerned with how environment and physiology affect tree growth as recorded within tree rings. The most basic principle of dendrochronology is that of crossdating, in which calendrical years are assigned to individual rings within a tree. Once crossdated, each ring is then a reflection of the climate or other environmental conditions that influenced that tree for that year.

The Annual North American Dendroecological Fieldweek is a workweek in applied tree-ring research, designed to give both beginners to the discipline an introduction to its basic methodology and applications and more experienced users a chance to work with and learn from others in the field in an informal group setting. The Fieldweek has had an outstanding history to date, with almost 250 participants in the five Fieldweeks from 1990 to 1994. The 6th Fieldweek is scheduled for 30 June to 8 July, 1995, at the Kananaskis Field Station in the Canadian Rockies near Calgary, Alberta.

**Abstract.**—The Annual Dendroecological Fieldweek is described. The Fieldweek is in its 6th year, with the 1995 event scheduled for Kananaskis Field Station near Calgary, Alberta.

## Format for the Fieldweek

The format for the Fieldweek is to break up into small research groups that examine a hypothesis that can be at least partially addressed using dendrochronological data (table 1). Each research group is led by an experienced dendrochronologist who serves as Principle Investigator for the project. The group poses questions concerning the central hypothesis and then spends the rest of the week collecting and analyzing both tree ring and other data designed to answer their questions. At the end of the week, groups get together to present their methods and results in an informal poster and oral session. Groups also write up their findings which are compiled into a final report. We also have a series of evening presentations and workshops during the week with topics ranging from different applications of dendrochronology to how to sharpen and care for an increment borer.

Without question, learning through experience has no equal. Since 1990, the Fieldweek has successfully challenged participants to explore new approaches to multi-disciplinary research. While we emphasize tree-ring research methods, we feel that

<sup>1</sup>Poster paper presented at the Interior West Global Change Workshop, April 25-27, 1995, Fort Collins, CO.

<sup>2</sup>Dendrochronologists, Rocky Mountain Forest and Range Experiment Station and Glacier Research Group, University of New Hampshire (respectively), and Co-directors of the North American Dendroecological Fieldweek.

**Table 1.—Locations, group leaders and group topics of the five fieldweeks from 1990 to 1994 and for the scheduled Fieldweek in 1995.**

**1990: Pinkham Notch, New Hampshire**

- David LeBlanc, Holcomb Research Institute, Butler University  
 "Analysis of growth of young red spruce on Mt. Washington, N.H."  
 Paul Krusic, USDA Forest Service, Northeastern Forest Experiment Station  
 "Soil erosion and tree root response along hiking trails in the White Mountains"  
 Charles Cogbill, Dartmouth College  
 "Forest history in spruce-fir"  
 Richard Phipps, US Geological Survey  
 "Long-term growth trends in high altitude red spruce, Mt. Washington, New Hampshire"  
 Gordon Jacoby, Lamont-Doherty Geological Observatory, Columbia University  
 "Using tree-ring analysis to date major flood events in the Saco and Culter-Ellis Rivers"  
 Ed. Cook, Lamont-Doherty Geological Observatory, Columbia University  
 "Reconstructing past beaver activity using tree-ring analysis"

**1991: H.J. Andrews Experimental Forest, Oregon**

- Malcolm Hughes, Laboratory of Tree-Ring Research, University of Arizona  
 "Gap formation and dynamics in old-growth Douglas-fir/hemlock stands"  
 Hal Fritts, Laboratory of Tree-Ring Research, University of Arizona  
 "Difference in climate signal between Douglas-fir and incense cedar chronologies"  
 Steve Leavitt, Laboratory of Tree-Ring Research, University of Arizona  
 "Dendrochronological investigations in the vicinity of Collier Glacier"  
 Elaine Kennedy-Sutherland, University of Utah  
 "Growth responses of *Populus* and *Alnus* to climate and disturbance"  
 Marion Parker, Forintek Canada  
 "Dating bark-stripped trees at Hidden Lake, Willamette Nat'l. Forest, Oregon"

**1992: Mountain Research Station, Colorado**

- Tom Swetnam, Laboratory of Tree-Ring Research, University of Arizona  
 "Fire and climate interactions in Left Hand Canyon, Colorado"  
 Gordon Jacoby, Lamont-Doherty Earth Observatory, Columbia University  
 "Dendrochronological dating of flood scars along the Big Thompson and Fraser Rivers"  
 Elaine Kennedy-Sutherland, USDA Forest Service, NE Forest Experiment Station  
 "History of an uncharacteristic lodgepole pine/aspen stand"  
 Dave Yamaguchi, Institute for Arctic and Alpine Research, University of Colorado  
 "Recent treeline migration on Rogers Peak, Colorado"  
 Dave Stahle, University of Arkansas  
 "Frost rings in bristlecone pine, Goliath Peak, Colorado"

**1993: Mountain Lake Biological Station, Virginia**

- Elaine Kennedy-Sutherland, USDA Forest Service, NE Forest Experiment Station  
 "Fire history of Table Mountain Pine, Brush Mountain, Virginia"  
 Dick Phipps, US Geological Survey  
 "Reconstructing flood history from tree rings"  
 Doug Larson, University of Guelph  
 "Dendroecological potential of *Juniperus virginiana* growing on cliffs in western Virginia"  
 Steve Stephenson, Fairmont State College, and Steve Adams, Lancaster Community College  
 "A dendroecological comparison of three red spruce populations"  
 Malcolm Cleaveland, University of Arkansas  
 "Earlywood and latewood chronology comparisons in conifers and hardwoods"

**1994: Southwestern Research Station, Arizona**

- Emilia Gutiérrez, University of Barcelona

"Stand dynamics in a ponderosa pine forest in Rustler Park, Chiricahua Mountains"

- Fritz Schweingruber, Swiss Federal Institute of Forest Research  
 "Look, wonder, and try to understand"  
 Henri Grissino-Mayer, Laboratory of Tree-Ring Research, University of Arizona  
 "Dendrochronological study of fire regimes in the Chiricahua Mountains"  
 Alex McCord, Laboratory of Tree-Ring Research, University of Arizona  
 "Dendrochronological methods to determine flood frequency in Pinery Canyon"  
 Ed Cook, Lamont-Doherty Earth Obs., Columbia Univ., and Keith Briffa, Univ. of East Anglia  
 "Standardization trials on Douglas-fir chronologies from Onion Saddle/Pinery Canyon"

**1995: Kananaskis Research Station, Alberta**

- Gordon Jacoby, Lamont-Doherty Earth Observatory, Columbia University  
 Ed Johnson, University of Calgary  
 Dan Smith, University of Victoria  
 Brian Luckman, University of Western Ontario  
 Dave LeBlanc, Ball State University

Fieldweek projects have effectively combined elements from many different disciplines to design novel solutions to ecological hypotheses. The Fieldweek attracts a diverse audience from disciplines from locations around the world, never stays in one place, and addresses research topics concerning all types of natural science. It is usually a very intense week, with a vast amount of work accomplished by dedicated participants who come to learn. Past Fieldweek projects have been published, used as bases for proposals to funding agencies, or formed core parts of theses or dissertations. In short, it is a unique learning experience for not only dendroecological methods, but also as a model for an interdisciplinary approach to answering problems facing us today.

### **Acknowledgments**

The Fieldweek has greatly benefited from financial support from a number of sponsors and funding agencies, not the least of which has been the US Forest Service through its Global Change Programs. The Interior West Global Change Program especially is to be thanked for its support of the 3rd Fieldweek in Colorado and partial funding for the 4th Fieldweek in Virginia. Other grants have come from the University of Arizona, the University of Arkansas, Oregon State University, Columbia University, the US Environmental Protection Agency, and the US State Department.

# Modeling Transient Response of Forest Ecosystems to Climatic Change<sup>1</sup>

Ned T. Nikolov<sup>2</sup>

## INTRODUCTION

Predicting transient response of forests to long-term changes in climate and atmospheric CO<sub>2</sub> concentration requires mechanistic models that couple tree population dynamics and disturbance regime with ecosystem cycles of carbon (C), water, and nitrogen (N) (Nikolov & Fox 1994; Bonan 1995). This linkage is essential because disturbance and forest demographic processes (i.e. birth, death and growth of trees) control spatio-temporal dynamics of the canopy structure and species composition that strongly impact carbon sequestration, soil nitrogen turnover, and transpirational water loss. The latter mechanisms feed back to population dynamics by modifying rates of individual tree growth, establishment, and mortality.

Three types of models have been applied in the past to project responses of forest ecosystems to climatic change: vegetation distribution models (VDM) (e.g. Neilson 1993), ecosystem flux models (EFM) (e.g. McGuire et al.

1993), and forest succession (also known as gap-phase) models (e.g. Solomon et al. 1986). Models of each category simulate different aspects of the ecosystem function but no one unites ecosystem flows of material and energy with vegetation population dynamics. Thus, VDMs only predict equilibrium response of forest biomes to climate since they do not incorporate dynamic processes and competitive species interactions. EFMs, in contrast, simulate steady-state ecosystem fluxes of C, N, and water assuming spatial homogeneity of the driving variables and constant vegetation characteristics (within a grid cell), i.e. they do not account for temporal variations in species composition and canopy leaf area index (Nikolov & Fox 1994). Gap models explicitly simulate successional changes in forest species composition and stand structure by keeping track of the birth, growth and death of individual trees on a number of discrete patches of ground representing forest landscape mosaics (e.g. Shugart 1984; Prentice & Leemans 1990). However, they use imprecise functions for describing tree physiological responses to environmental conditions, and do not employ robust C, N and water mass-balance principles (Nikolov & Fox

1994). As a result, traditional gap models predict rather poorly site-specific tree growth (Desanker et al. 1994) which makes them unsuitable for climate impact studies.

A recognition of the limitations of existing forest models led several researchers around the world to launch efforts towards developing a new-generation of hybrid ecosystem-population models (e.g. Friend et al. 1993; Nikolov & Fox 1994). This project is an example of such an activity. The goal is to produce a coupled carbon-water-nutrient-vegetation model that incorporates the state-of-the-art knowledge about critical ecosystem processes, and, thus, can be used with confidence to assess the consequences of a climatic change on the dynamics of temperate forests.

## METHOD

Nikolov & Fox (1994) outlined the general structure of a generic TEMperate Forest Ecosystem Simulation (TEMFES) model. Its concept is based on the notion that one needs to couple a whole tree carbon allocation model with a biophysical canopy gas and energy exchange model and a soil water and nutrient cycling model in the context of a forest gap-

<sup>1</sup>Poster paper presented at the Interior West Global Change Workshop, April 25-27, 1995, Fort Collins, CO.

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phase model in order to produce a simulation tool capable of linking short-term tree physiological responses to long-term successional dynamics of forests.

The C allocation and canopy gas-exchange models are responsible for making annual tree growth consistent with diurnal and seasonal variations of atmospheric drivers. The soil model keeps track of the infiltration, flow, drainage, and runoff of water in the soil profile, as well as of the snow melt and the vertical soil heat fluxes. A separate part of the soil model simulates organic-matter decomposition and N mineralization. The soil and biophysical models work in concert to provide estimates of the dynamics of soil moisture and nitrogen availability within the soil profile that are used to con-

strain the tree physiological model. Tree species physiology is also controlled by air temperature, solar radiation, atmospheric humidity, and CO<sub>2</sub> concentration. These models serve to compute annual growth, establishment, and mortality of individual trees on a number of discrete patches of ground representing the spatial heterogeneity of a forest landscape. The patch size is a function of latitude and the expected average stand height at maturity. For the temperate region, it is about 0.1 ha (Shugart 1984). Figure 1 depicts the main parameters and processes and their interactions controlling patch-scale forest dynamics in the TEMFES model. Ecosystem dynamics is computed as the average of the dynamics of many individual patches.

## RESULTS

### Leaf Photosynthesis Model (LEAFC3)

Nikolov et al. (1995) combined data and relationships from leaf physiology, physics, and fluid mechanics to develop a generic model (LEAFC3) for estimating short-term fluxes of CO<sub>2</sub>, water vapor, and heat from broad leaves and needle-leaved coniferous shoots of C<sub>3</sub> plants. The model explicitly couples the leaf's major biochemical reactions with stomatal function and leaf-boundary layer heat- and energy-exchange mechanisms providing a mechanistic link between CO<sub>2</sub> uptake and transpirational water loss (fig. 2). Table 1 summarizes model input parameters and output variables. The algorithm implements a highly optimized solution technique that allows LEAFC3 to be directly incorporated into plant canopy models.

LEAFC3 has been parameterized and tested using measured photosynthesis and stomatal conductance data for lodgepole pine, quaking aspen, and limber pine. A sensitivity analysis has demonstrated that the model is capable of reproducing a number of observed leaf-environmental relationships that have not been explicitly coded into its structure.

The LEAFC3 model has been applied to study the environmental and physiological regulation of leaf water-use efficiency (WUE, a ratio of net CO<sub>2</sub> assimilation rate to transpiration) under equilibrium conditions. Simulation results suggest that:

### TEMFES MODEL

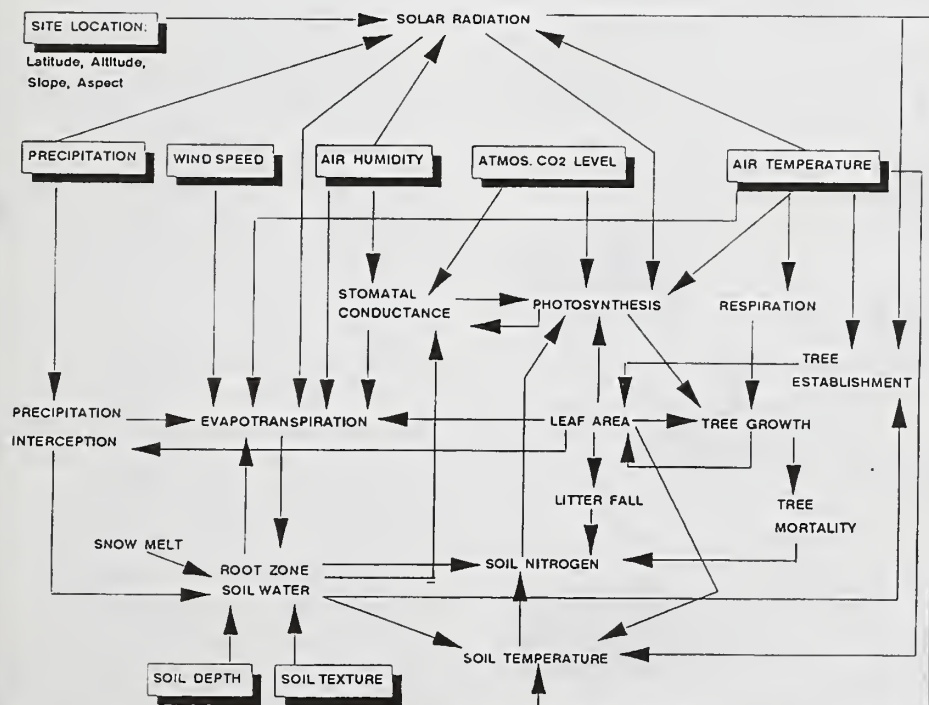


Figure 1.—Main parameters and process controlling forest ecosystem flows and population dynamics in the TEMFES model. Arrows indicate interacting processes.



step, the flow model is run for all individual columns which is followed by an area-weighted averaging of the output to yield mean soil water and heat fluxes at the field-scale.

The effect of soil moisture on stomatal conductance and transpiration is modeled employing recent findings and algorithms on the interaction between plant hydraulic and hormonal signals (i.e. plant water potential and abscisic acid) (e.g. Tardieu et al. 1993).

The novel aspects of the FOR-FLUX model compared to numerous biophysical models developed during the past decade can be summarized as follows:

- 1 Canopy fluxes are estimated by a spatio-temporal integration of a model (i.e. LEAFC3) that mechanistically couples photosynthesis and transpiration at the leaf level (solving exactly the leaf energy balance equation). This is a much better approximation of the physical reality than the use of single- or multiple-source formulations that separate these processes.

- 2 Soil heat- and water-transport is modeled employing robust physical principles and explicitly accounting for the effect of soil heterogeneity on the field-scale fluxes. This approach is considerably more vigorous than the 'soil-bucket' approximations commonly used in ecosystem models.

**Table 1.—Input parameters and output variables of the LEAFC3 model (Nikolov et al. 1995).**

Parameter	Description	Units
<i>Species-specific input parameters</i>		
$V_{m25}$	Maximum carboxylation velocity at 25°C	$\mu\text{mol m}^{-2} \text{s}^{-1}$
$J_{m25}$	Light-saturated potential rate of electron transport at 25°C	$\mu\text{mol m}^{-2} \text{s}^{-1}$
$K_{c25}$	Kinetic parameter for $\text{CO}_2$ at 25°C	mol/mol
$K_{o25}$	Kinetic parameter for $\text{O}_2$ at 25°C	mol/mol
$f$	PPFD loss factor	—
$m$	Composite stomatal sensitivity to net photosynthesis, leaf- surface humidity and $\text{CO}_2$ concentration.	—
$b_{sv}$	Empirical constant for stomatal conductance	$\text{mol m}^{-2} \text{s}^{-1}$
$d$	Leaf width (or needle diameter)	m
$d_o$	Shoot diameter (for conifers only)	m
$Y_{crit}$	Critical leaf water potential for stomatal closure	— MPa
$n$	Power term used in the relationship between stomatal conductance and leaf water potential	—
$Y$	Leaf water potential	— MPa
<i>Environmental input parameters</i>		
$P$	Atmospheric pressure	Pascals
$c_o$	Ambient $\text{CO}_2$ concentration	mol/mol
$O_a$	Ambient $\text{O}_2$ concentration	mol/mol
$T_a$	Ambient air temperature	°C
$RH$	Ambient relative humidity	%
$R_i$	Bi-directional absorbed short- and long-wave radiation by the leaf	$\text{W m}^{-2}$
$Q$	Incident photosynthetic photon flux density	$\mu\text{mol m}^{-2} \text{s}^{-1}$
$u$	Horizontal wind speed	m/s
$L_{ws}$	Leaf wetness status	0 = dry; 1 = wet
<i>Output variables</i>		
$a_n$	Net $\text{CO}_2$ assimilation rate	$\mu\text{mol m}^{-2} \text{s}^{-1}$
$g_s$	Stomatal conductance to water vapor	$\mu\text{mol m}^{-2} \text{s}^{-1}$
$g_b$	All-sided leaf-boundary layer conductance to water vapor	$\mu\text{mol m}^{-2} \text{s}^{-1}$
$T_l$	Leaf temperature	°C
LE	Latent heat flux	$\text{W m}^{-2}$

- 3 The effect of root chemical signaling on stomatal conductance is modeled allowing for a simulation of the interaction between transpiration rate and stomatal sensitivity to adverse soil conditions such as drought or freezing.

- 4 Coupling of a detailed canopy-process model with a stochastic soil-water flow model has not been attempted thus far to our knowledge in any forest modeling study. We expect that this approach will further our understanding about forest ecosystem function by providing new insights on soil-canopy interactions.

The purpose of the FORFLUX model in the context of the current project is (i) to explore the relationship between short-term meteorological variability and long-term (seasonal to multi-year) dynamics of carbon gain and water loss by forest ecosystems; (ii) to study the sensitivity of major ecosystem fluxes to changes in forest canopy structure, soil physical characteristics, seasonality, and atmospheric CO<sub>2</sub> concentration; and, finally, (iii) to assist in deriving computationally efficient (phenomenological) algorithms for simulation of key ecosystem-climate interactions in forest succession models. The model currently is being tested and debugged.

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**Table 2.—Input parameters and output variables of the FOFLUX model.**

### Input parameters

#### *Site characteristics*

- Latitude (deg)
- Altitude (m a.s.l)
- Slope inclination (deg)
- Slope aspect (deg)

#### *Meteorological data*

- Julian day
- Incident short-wave radiation (W m<sup>-2</sup>)
- Air temperature (°C)
- Relative humidity (or dew point temperature) (% or °C respectively)
- Precipitation amount (mm)
- Horizontal wind speed above the canopy (m/s)

#### *Soil parameters*

- Total soil depth (m)
- Rooting depth (i.e. the soil depth containing 95% of the root biomass) (m)
- Bulk density (g cm<sup>-3</sup>)
- Percent clay and sand
- Percent organic carbon
- Presence of a water table (Yes or No)
- Three parameters characterizing the lognormal probability density function of saturated hydraulic conductivity at the field scale.

#### *Vegetation structural parameters*

- Total stand leaf area index (m<sup>2</sup> m<sup>-2</sup>)
- Percent of branch area index in the total LAI
- Foliage clumping factor (dimensionless)
- Mean inclination angle of the foliage elements (deg)
- Mean leaf width (or needle diameter) of mature leaves (m)
- Mean shoot diameter (for conifers only) (m)
- Above-ground sapwood biomass (g m<sup>-2</sup>)
- Root biomass (g m<sup>-2</sup>)
- Mean nitrogen concentration of the sapwood biomass (%)

- Mean nitrogen concentration of the root tissue biomass (%)
- Average root-length density in the top 5 cm of the soil profile (m m<sup>-3</sup>)
- A parameter describing the rate of exponential decline of root-length density with depth (m<sup>-1</sup>)

#### *Vegetation physiological parameters*

- Leaf maximum carboxylation velocity at 25°C (μmol m<sup>-2</sup> s<sup>-1</sup>)
- Leaf light-saturated potential rate of electron transport at 25°C (μmol m<sup>-2</sup> s<sup>-1</sup>)
- Leaf kinetic parameter for CO<sub>2</sub> at 25°C (mol/mol)
- Leaf kinetic parameter for O<sub>2</sub> at 25°C (mol/mol)
- Photosynthetic photon flux density loss factor of leaves (-)
- Composite leaf stomatal sensitivity to net photosynthesis, leaf-surface relative humidity and CO<sub>2</sub> concentration (-)
- Parameter defining the exponential decline of maximum Rubisco activity and potential rate of electron transport with canopy depth.
- Three parameters describing leaf stomatal response to root water potential and transpiration rate.

### Output variables

- Net canopy CO<sub>2</sub> uptake rate
- Canopy transpiration (latent heat flux)
- Canopy precipitation interception
- Above-ground woody maintenance respiration
- Root maintenance respiration
- Total soil CO<sub>2</sub> flux
- Soil surface evaporation
- Deep soil water drainage
- Soil surface runoff
- Mean volumetric moisture content of the rooting zone
- Mean soil temperature of the rooting zone
- Spatially averaged soil surface temperature
- Spatially averaged soil heat flux

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# Incipient Weathering and Soil Development in Ash Deposits from the Mount St. Helens Eruption of 1980<sup>1</sup>

James L. Clayton<sup>2</sup>

## Introduction

The abundance of volcanic ash that has been deposited in the Pacific Northwest has provided a natural laboratory to study ash deposits geologically, morphologically, and chemically. Mineralogically distinct deposits from several origins (Glacier Peak, MSH, Mt. Mazama) and dating back to ca. 20,000 years b.p. have been identified in Idaho and Montana. Tephra from Mazama and MSH deposited over the last 6,700 years are sufficiently thick and distinct to be useful over widespread areas for soil morphology and chemistry studies. In 1980 our work unit funded and participated in a study of tephra deposited in forest openings in northern Idaho and western Montana as a result of the May 18 eruption of MSH. This study included detailed descriptions of mineralogical and chemical properties of soil and ash deposits along a 250 km by 100 km transect (roughly between Moscow and Missoula) at 94 locations (Fosberg et al. 1982). Over 100

samples of 1980 tephra and soil horizons including other well-dated ash fall events (MSH-T, MSH-Y, and Mazama) were collected and archived in Boise as part of this study. All sampling site locations were documented for re-sampling. This provided an opportunity to compare short duration field weathering data on fresh minerals (1980) to other deposits of comparable mineralogy over the past 6,700 years (through Mazama) using surface chemistry techniques (scanning electron microscopy (SEM) and energy dispersive analysis of x-rays (EDX)) that have proven useful in our previous lab and field studies. In addition, very short-term soil profile development including ash incorporation in surface soil horizons and organic matter recruitment to ash deposits was investigated for a geographically broad suite of forest soils. The specific objectives of this research were to: 1. Test the hypothesis that soil development over the 11 year period between sampling resulted in organic C buildup and loss of extractable cations from MSH-1980 deposits; and 2. Document and quantify changes in surface chemistry, grain morphometry

**Abstract.**—Surface ash has mixed with and become incorporated in forest floor material, and organic matter content and rooting frequency have increased. The saturation paste pH of the ash decreased by 0.6 units, however the pH in NaF was not significantly different. Exchange acidity, exchangeable cations, and CEC were all significantly higher in the 1991 samples, but there was no change in base saturation. SEM observation of selected grains showed little change with time. XPS analysis showed higher surficial O, Ca, and Al contents, with a concurrent decrease in Na. EDX analysis also revealed Na depletion.

and clay mineralogy resulting from *in-situ* weathering of MSH-1980 ash.

Samples collected in 1980 come from a geographically and ecologically diverse selection of forested sites in northern Idaho and Montana. Available data include: soil profile and site (habitat types, landforms, climate etc.) descriptions, soil chemical analyses, and detailed mineralogical descriptions of ash deposits. Ash characterization includes petrographic and x-ray diffraction studies and elemental analysis by scanning electron microprobe and neutron activation analysis. The value of these baseline data is enhanced by the archived samples that were collected in the summer and fall of 1980. These samples have been preserved in sealed containers since their collection.

Although the sampling was conducted within five months of the May eruption, consolidation and/or redistribution of fresh ash resulted in average depths that were < 50% of depths reported immediately following the eruption (Sarna-Wojcicki et al. 1981). Soluble cations (saturation paste) and exchangeable cations were atypically high on 1980 MSH samples when compared to MSH-

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T (150-200 years b.p.) and Mazama. Mineralogically, MSH 1980 was similar to previous MSH deposits, however plagioclase was somewhat more anorthitic (andesine/labradorite) than previous eruptions. The dominant mineralogy of the clay sized fraction (<2  $\mu\text{m}$ ) is smectite. This mineral originated from numerous hot spots and steam vents prior to the eruption and was carried with the internal melt ejecta during the eruption. Smectite is of particular interest because it is not the clay mineral being formed by present day pedogenic processes in the forested sites in northern Idaho and Montana. Mazama and MSH-T clay fractions contain approximately equal amounts of smectite and vermiculite.

## Methods

Field sampling repeated the original sampling techniques as far as possible. Original soil samples and profile descriptions were obtained from a single soil pit, centrally located at each site. Six hundred to eight hundred grams of soil, composed of the same horizons but as a composite from 4 pits located at random 90-degree azimuths, 2 m distant from the original pit, were collected. Complete profile descriptions to the depth of the lowest clearly defined ash layer (usually Mazama) were made, however only ash horizons were collected.

Laboratory chemical analysis methods matched the methods used on the 1980 samples. These included: organic carbon (Walkley-Black digestion), pH (saturation paste and NaF), extractable

bases (neutral, 1 M  $\text{NH}_4\text{OAc}$ ), and exchangeable acidity ( $\text{BaCl}_2$ -TEA). All these methods are described in American Society of Agronomy (1982).

Mineralogical analyses included: scanning electron microscopy (SEM) and energy dispersive x-ray analysis (EDX) of fine sand, very fine sand, and silt fractions of selected samples, and x-ray diffraction (XRD) analysis of clay fractions. XRD samples were Mg saturated and ethylene glycol solvated, and K saturated with and without heat treatment at 500  $^{\circ}\text{C}$  for 2 hours. In addition, the surface chemistry of tephra samples was characterized using x-ray photoelectron spectroscopy (XPS). Ash subsamples were mounted on double stick tape to adhere to tantalum metal bases. The average elemental surface composition of an approximately 8  $\text{mm}^2$  area was analyzed. Six sweeps were conducted for each of the following photoelectrons: O1s, NaKLL, Ca2p, Al2s, Si2s, Si2p, and MgKLL. Three complete repetitions were run on each sample and the resultant peaks were manipulated by deglitching and smoothing. Peak areas were determined by processing the peaks through an integration routine.

An analysis of variance and Newman-Keuls comparison test at  $\alpha = 0.05$  was used on 1980, archived, and 1991 samples to test the hypothesis that soil development changed cation exchange capacity, exchangeable cations, and soil pH. SEM, organic matter accretion, and rooting frequency observations were used descriptively to document change. Evidence of mineral weathering by XPS was determined by alkali

and alkaline earth element depletion when comparing archived and 1991 samples. XRD analysis of clays was used to semi-quantitatively document changes in mineralogy arising from weathering of smectite to vermiculite or mixed layer clays.

## Results

All sites sampled in 1991 had litter present and live vegetation growing through the 1980 ash deposits. Mean percent organic carbon increased from 0 to 4.1% over the 11-year period, and ranged from 0.3% to 11%. Soil scientists describe root frequency and size in the field using class data. Field descriptions of rooting in the ash layers ranged from few fine, to common fine or common medium. Fine roots range in size from 0.5-2 mm, and the modifier "few" indicates less than 10 per square decimeter; "common" indicates 10 to 50 roots per square decimeter. Common medium roots indicates 1 to 5 per square decimeter with a diameter range of 2 to 5 mm. Organic carbon additions to the tephra deposits resulted from litter additions, live vegetation establishment indicated by the presence of stems and roots in the ash, and through surface mixing by animals.

There were distinct changes in the pH and exchange fraction chemistry during the 11-year period of soil development. (All changes reported are statistically significant). The saturation paste pH of samples decreased by 0.6 pH units, from an average value of 6.2 in 1980 to 5.6 in 1991. There was no difference in archived sample and 1980 saturation paste

pH values. There were no differences between 1980, archived, and 1991 pH values measured in 1 M NaF.

Exchangeable K, Ca, and Mg in ash increased over the 11-year period; however exchangeable Na decreased. The net effect of these changes was an approximate 4X increase in exchangeable bases. Exchange acidity doubled and cation exchange capacity increased from 6 to 16 cmol kg<sup>-1</sup> over the same period. There was no change in base saturation because of weathering and soil development. It is likely that increases in exchange capacity and cations resulted from organic matter additions to the ash deposits.

XPS analysis of the 1991 samples showed higher surficial O, Ca, and Al content than archived 1980 samples. A concurrent decrease in surface Na was observed for all samples. EDX analysis of individual glass shards also revealed depletion of Na relative to other elements but showed no overall increase in either Ca or Al. In general, previous studies of incipient weathering of fresh minerals have shown selective depletion of surficial Ca and Na (Schott and Pettit, 1987; Nesbitt and Muir, 1988). Thus, the increase in Ca observed by XPS analysis of the bulk sample suggests a process other than weathering is responsible for the changes in surface chemistry. One possible explanation is that the ash received Ca from non-tephra material through mixing, nutrient cycling, or precipitation.

Extensive observations of glass shards with SEM did not reveal any chemical weathering features such as clay coatings or etch pits.

There was some rounding and smoothing of rough, jagged edges that are common on the archived samples but this may be because of physical abrasion rather than chemical weathering. There were no changes in the composition of clay when comparing archived and 1991 samples using XRD. Smectite is still present and in approximately equal amounts when comparing the two tephra sets.

Overall, only slight chemical weathering of the tephra was detected. The most significant changes were found using XPS, the most surface sensitive of the chemical techniques used. Research has shown that alteration of the mineral matrix by weathering processes are initiated at the outer-most surfaces (e.g. 10-100 Å), and with time, proceed deeper into the structure. With more intensive weathering, features such as etch pits and clay coatings develop. The 11-year weathering period was apparently not intensive enough to produce physical weathering features or changes in clay mineral content as observed by SEM and XRD. However, Na depletion at the surface indicative of initial chemical weathering can be detected in 11 years.

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# Genetic Variation, Climate Models and the Ecological Genetics of *Larix occidentalis*<sup>1</sup>

Gerald E. Rehfeldt<sup>2</sup>

**Abstract.**—Provenance tests of 138 populations of *Larix occidentalis* revealed genetic differentiation for eight variables describing growth, phenology, tolerance to spring frosts, effects of *Meria laricis* needle cast, and survival. Geographic variables accounted for as much as 34% of the variance among Rocky Mountain populations. Patterns of genetic variation were dominated by the effects of latitude and elevation, with populations from the north and from high elevations having the lowest growth potential, the least tolerance to the needle cast, and the lowest survival. However, the slope of the geographic clines was relatively flat. Populations in the same geographic area, for instance, need to be separated by about 500 m in elevation before genetic differentiation can be expected.

## Introduction

This paper deals with the environmental bases for genetic differentiation in western larch (*Larix occidentalis*), a species distributed across 7° of latitude and 1500 m of elevation. Genetic variation among populations first is assessed for traits reflecting growth potential, disease resistance and survival in common gardens. Next, models are developed that describe the general climate for the region sampled by the provenances under study, and finally, ecological genetics of western larch is considered as a synthesis of the genetic and climatic information.

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## Procedures

### Genetic Variation

Wind-pollinated seeds from 138 provenances of western larch were compared in common gardens. Periodic measurements and scores were recorded for: (1) total height (cm) at age 3; (2) presence or absence of winter freezing damage to the wood or buds on the 2-year shoot; (3) presence or absence of spring frost damage to developing long shoots in year 3; (4) rate of elongation (cm/week) of the 3-year shoot between June 1 and July 20; (5) late growth, the amount (cm) of the 3-year shoot that elongated after August 13; (6) incidence of *Meria* needle cast; (7) tolerance to *Meria* needle cast, measured as the residual from the regression of 4-year height on 3-year height; (8) survival at the beginning of year 5.

Statistical analyses of population differentiation were completed in two stages: (1) analyses of variance to assess the degree of differentiation, and (2) multiple

regression analyses for describing patterns of variation from polynomial models using latitude, longitude, and elevation as predictors.

### Climate Models

Weather data were assembled from 192 weather stations that (1) best represented the Rocky Mountain portion of the distribution of western larch and (2) had at least 10 years of records. To remove the effects of long-term trends in weather records of differing length, only those data collected after 1940 were considered for United States stations. However, comparable daily weather records were not readily available for stations in British Columbia. Instead, mean values for the period from 1951 to 1980 were provided by the Research Branch, British Columbia Forest Service. Mean values for United States stations were calculated from daily records available from Earthinfo, Inc. (1994). In using data from the latter source, the

records from a station were discarded for all years missing more than 20% of the daily observations.

The weather variables under consideration were mean annual temperature, mean temperature in the coldest month, mean temperature in the warmest month, mean number of frost-free days, mean length of the frost-free period, mean annual precipitation, mean precipitation in the summer months (May-September), mean precipitation in the driest month, mean precipitation in the wettest month, and the ratio of summer precipitation to the mean annual precipitation. Multiple regression was used to develop models of climate variation for each of the 10 variables. The resulting models thus allowed general features of a local climate to be predicted from latitude, longitude, and elevation.

### Environmental Basis for Genetic Differentiation

The climate models were used to predict 10 general climatic features for the 138 Rocky Mountain provenances represented in the tests of genetic variation. The relation between genetic variation and the climate was assessed by using stepwise regression to find the best one- or two-variable models.

## Results

### Genetic Variation

Analyses of variance detected significant differences among Rocky Mountain provenances for

all variables except winter freezing damage. Thus, mean differences among provenances also tended to be large: 63 cm in 3-year height; 72% in the number of trees damaged by the spring frost; and 15 cm in the amount of late summer shoot growth. Populations were differentially affected by *Meria* needle cast: by 18% in the percentage of seedlings heavily infected, and by 73% in mortality.

Despite the large mean differences, variance components suggested that the amount of differentiation was relatively low; effects of provenances accounted for as much as 13% of the total variance, but averaged less than 6%. Sampling errors contributed 52% to 92% of the total variance, explaining how differentiation could be relatively weak despite large mean differences among populations.

Multiple regressions using geographic predictors accounted for statistically significant proportions of the genetic variance for each of the seven variables for which differentiation had been detected. Values of  $R^2$  ranged from 0.14 to 0.34, accounting for 30% or more of the variance among populations for three variables associated with response to the needle cast.

Geographic variation was most closely related to provenance elevation. The regressions showed that as elevation increased, 3-year height, *Meria* tolerance, rate of shoot elongation, amount of late growth, and survival decreased, while *Meria* incidence increased. Rates of differentiation across the landscape were interpreted from the ratio of the regression coefficient

describing the slope of a cline to an error statistic, the least significant difference at the 0.2 level of probability. This ratio provides the elevational interval that must separate populations within the same general locality before there is a reasonable possibility of genetic differentiation: 509 m for survival, 570 m for 3-year height, 712 m for late growth, 715 m for the incidence of *Meria*, 719 m for rate of shoot elongation, and 740 m for *Meria* tolerance.

When geographic variation is considered for a constant elevation, growth potential, as measured by either the rate of elongation or 3-year height, increased from northwest to southeast across the study area. Northern populations, moreover, had the highest incidence of and lowest tolerance to *Meria* needle cast at the Priest River site. Populations from the south produced the most late growth, suffered the least from the needle cast, and had the highest survival. Like the elevational clines, however, rates of differentiation along the geographic clines are relatively gentle. In fact, all of the geographic variation throughout this vast region could be represented by three discrete zones, a northwestern, a central and a southeastern.

### Climate Models

Regression analyses using geographic independent variables were particularly effective in describing variation in the five variables controlled by temperature. Values of  $R^2$  were as high as 0.92 for the mean annual temperature, ranging down to 0.63 for

the length of the frost-free period. Values of  $R^2$  for precipitation variables were generally lower, ranging from 0.57 for the mean summer precipitation to 0.46 for the mean precipitation in the wettest month.

The elevation of the weather station was an integral part of the models for all variables. The results showed that all temperature variables had a nonlinear relationship with elevation, with the steepness of the slope decreasing at the higher elevations. The models showed that for elevations from 500 to 1500 m, the mean annual temperature decreases by about 6°C per 1000 m while the frost-free period decreases by about 90 days. Above 1500 m, however, the mean annual temperature continues to decrease while the length of the frost-free period changes little. The regressions also showed that for the elevational range of 500 to 1500 m, the number of days without frost decreases by about 100, the mean temperature in the warmest month decreases by 6.5 degrees, and the mean temperature in the coldest month decreases by 4.5 degrees.

All precipitation variables except the ratio of summer to total precipitation showed a linear and positive association with elevation. Across 1000 m, for instance, mean annual precipitation tends to increase by 35.5 cm, the mean precipitation in the warmest month increases by 4.5 cm, and the mean precipitation in the driest month increases by about 1 cm. In contrast, the ratio of summer precipitation to mean annual precipitation decreased by about 0.03 across 1000 m.

Geographic trends described by the models for an elevation of 870 m, the mean elevation of all weather stations, showed strong influences of latitude and the position of both the Rocky Mountains and the Cascade Range. Patterns for the number of days without frost, the mean annual temperature, and the length of the frost-free season showed that when comparisons are made at a constant elevation, the warmth of the climate during the growing season increases toward the south and east. While the same latitudinal trends are apparent for the mean temperature in the coldest month, patterns for this variable also suggested that the climate at a constant elevation becomes more severe toward the east. In this region, therefore, as one approaches the Rocky Mountains from the west, the climate at a constant elevation becomes warmer during the summer and colder during the winter.

Patterns of variation in precipitation variables predicted for a constant elevation generally reflected (1) rain shadows produced by the course of westerly storm tracks across the Cascade Range and the Rocky Mountains, and (2) the wet belt of southeast British Columbia. The models showed that precipitation increases as the Rocky Mountains are approached from the arid climates of central Oregon and Washington. As the Rocky Mountains are crossed, annual precipitation not only decreases greatly but also is dominated by the effects of summer storms; the area east of the Rocky Mountains, therefore, has the highest ratio of summer precipitation to total precipitation.

## Climatic Control of Differentiation

Climate models were used to predict general conditions at each western larch provenance sampled in the studies of genetic variation. To the extent that these provenances represent the natural distribution of the species in the Rocky Mountains, predicted climates provide the best estimates of the environmental conditions under which western larch occurs: wherever the mean annual temperature is between 2 and 8°C; the mean temperature in the coldest month is above -10°C; the mean temperature in the warmest month is below 19°C; the total number of days without frost is between 123 and 206; and the total precipitation is between 37 and 102 cm, with 25% to 50% coming in the summer months.

Western larch trees from a particular provenance are expected to be genetically suitable for only a portion of the environmental conditions across which the species as a whole is distributed, however. To elucidate the environmental tolerances of specific populations, patterns of genetic variation were described from predicted climatic effects. Statistically significant one-variable models were found for all genetic effects except spring frost damage. All significant one-variable models implicated the relative mildness of the climate as the primary factor controlling genetic differentiation. Either the mean annual temperature or the total number of frost-free days, two variables related by a simple correlation of 0.85, appeared as the best predictors. The relative effectiveness of climatically based

models relative to the geographically based models is expressed in the ratio of the respective values of  $R^2$ . One-variable climatically based models accounted for 44% to 87% of the variance attributed to the geographically based models. The highest ratios were associated with innate growth potential as expressed in the rate of shoot elongation and 3-year height, while the lowest involved *Meria* incidence and tolerance.

The two-variable models, which were developed from programs that retained the best single variable, augmented  $R^2$  by an additional 3% to 8%. This meant that the best climatically based models were accounting for 68% to 100% of the variance attributable to the geographically based models. The significant two-variable models each added an independent variable describing the precipitation regime. Of these precipitation variables, the mean precipitation in the dry month appeared in two of the models, while mean annual precipitation appeared in three. The greatest impact of a second variable was on *Meria* incidence and tolerance and, therefore, on survival.

The models showed that as the mildness of the climate increased, so did growth potential, the ability to withstand *Meria*, and, therefore, survival. High precipitation, whether measured as total annual precipitation or as mean precipitation in the driest month, tended to be associated with a high growth potential, reduced effects of *Meria*, and high survival.

The results suggest that genetic differentiation (relative to LSD 0.2) tends to be associated with

environmental intervals of 28 days in the total number of frost-free days, 2.6°C in mean annual temperature, 40 cm in mean annual precipitation, and 1.5 cm in precipitation in the driest month. These results further suggest that the trees in a single population are genetically suited to temperature intervals representing about 44% of the total gradient occupied by the species; for the number of frost-free days, the interval is 34%, and for the precipitation variables the interval is about 60%. Populations of similarly adapted individuals thus are broadly dispersed. The extent to which this broad dispersal results from high phenotypic plasticity of individual trees or from high genetic variability within populations (low or variable selection intensities) cannot yet be discerned.

Nevertheless, the results demonstrate that patterns of genetic variation described by geographic variables relate directly to environmental variables that plausibly reflect the effects of natural selection.

### Applications

Models of genetic variation with geographic predictors have many uses in forest management, conservation biology, and in understanding the potential effects of climate change. Yet, the validity of such models requires that the relationship between geographic variables and the climate is static, and that the models are used within the region for which they were developed. Prohibiting extrapolation, however, means that such

models are not valid in a changed environment. Because of this, models that incorporate climatic predictors not only offer ready ecological interpretations, but also extend the applicability and versatility of geographically based models.

The primary application of genecological investigations is to guide seed transfer in artificial reforestation such that planted trees will be adaptationally similar to the natural population. The results suggested that the transfer of western larch seeds from a single source should be limited both elevationally and geographically. Such restrictions correspond to limiting seed transfer into environments differing from that at the seed origin by no more than (1)  $\pm 1.3^\circ\text{C}$  in mean annual temperature, (2)  $\pm 14$  frost-free days, (3)  $\pm 20$  cm in mean annual precipitation, and (4)  $\pm 0.75$  cm in mean precipitation in the driest month.

While limiting seed transfer according to geographic variables is doubtless most convenient to managers, changing conditions require environmental descriptors. Introduction of species or populations into foreign environments requires an understanding of ecological tolerances. Localities with climates within the ranges described above, for instance, are potentially suitable for the introduction of western larch. An appropriate population also could be selected by using models with climatically based predictors.

The effects of climate change on adaptedness also can be addressed from climatically based models. Daily weather records at the Priest River Experimental Forest show that the climate has

gradually ameliorated since 1912. Compared to the first 15 years of records, the climate in the last 15 years, for instance, has 30 more frost-free days. This change suggests that the climate in 1912 was similar to today's climate at elevations 300 m higher. Because much of the experimental forest burned during the early part of the 20th century, current forests are no longer optimally adapted to contemporary environments. This situation, described as an adaptational lag, arises because natural selection is retrospective: current levels of adaptedness have developed from environmental selection in the past.

Because of the shift in climate, trees used for reforestation at Priest River should be genetically attuned to a milder environment than the populations established in 1912. The models suggest that maintaining optimal growth and productivity from reforestation requires that seeds produced by the 1912 population at 725 m (the valley floor) be planted between 775 and 1275 m  $[(725+300)\pm 250]$ . Likewise, planting a site at 725 m should use seeds either from nearby sites at elevations lower than 675 m, or from elevationally similar sites approximately 2° of latitude to the south.

Similarly, predictions for global climate change suggest that mean annual temperatures in the middle latitudes may increase by about 5°C. Since genetic differences among western larch populations occur in association with temperature differentials of about 2.6°C, accommodating a climate change of 5°C will necessitate wholesale redistribution of genotypes across the landscape. Because the mean annual temper-

ature changes by about 6°C across 1000 m, a change of 5° suggests that climates similar to the present will be found at elevations 833 m higher than today. After such a change, seeds produced by the 1912 population at 725 m should be used for reforestation after climate change at elevations between 1300 and 1800 m  $[(725+833)\pm 250]$ . Similar calculations suggest that no appropriate natural populations currently exist for reforesting the site at 725 m. Indeed, the current mean annual temperature at this elevation at Priest River is about 5.6°C. An increase of 5°C would produce a mean annual temperature exceeding that associated with the current ecological distribution of the species.

The applications of this study illustrate the potential value of understanding the ecological basis of genetic variation. The union of geographically based and climatically based models thus provides an additional link in understanding adaptation of populations of broadly distributed species. Once the links are understood, models become more creditable, flexible, and applicable.

# Assessing the Effects of Changing Climate on Mountain Pine Beetle Dynamics<sup>1</sup>

J. A. Logan, P. V. Bolstad, B. J. Bentz, D. L. Perkins<sup>2</sup>

Climate and weather have profound effects on insect life systems. As poikilothermic organisms, essentially all life processes are directly related to temperature. Other weather related climatic variables also influence population performance and ultimately determine persistence as a species. In temperate climates, basic adaptations such as maintaining an appropriate seasonality must be keyed to prevailing weather. Any changes in weather, and in particular

climate, should be of basic interest to insect ecologists. Given this importance, it is somewhat surprising that relatively few publications have seriously treated the potential effects of climate change on specific insect populations (e.g. Sutherst, 1989; Porter et al., 1991). Perhaps one of the reasons for this dearth of entomological research is that empirical demonstration of climate change is difficult indeed. In the northern Rocky Mountains, for example, the summer of 1993 will be remembered as all-in-all a pretty mild winter. This, of course, during a time of supposed global warming. The world is a noisy place, and the global climate system is exceedingly complex. Both of these facts render empirical, statistical differentiation of long-term trends from short-term cycles to be essentially impossible. This creates an interesting dilemma. We cannot state, with any degree of certainty, that climate change is actually taking place. On the other hand, the issues in question are so basic to life on earth, can we afford to wait for irrefutable empirical confirmation? In general terms, both the world scientific and political communities have determined that the magnitude of risk justifies expenditure of

substantial resources to address this potential ecological peril.

As a direct result of the difficulty of empirical experimentation with a system as unwieldy as the global climate, a significant and basic foundation to global climate research has been the development of models to predict the effects of factors such as anthropogenic greenhouse gases. The role of models in situations of high uncertainty and high risk may be to provide the best chance of a crystal ball that in some sense portends the future. Models of global climate [the so called Global Circulation Models (GCMs)] have, in fact, proliferated over the past few years. At the present time, there are at least 20 major GCMs (Kickert, 1993). Given the complexity of the modeled system, it is not surprising that so many models have been developed. It is also of little surprise that these models disagree in many important predictions. In particular, there are substantial differences regarding patterns of climatic variability, rainfall and moisture distributions, modified seasonality, etc. All of these models, however, have one important commonality. They all agree that substantial global warming will take place, and that this warming will occur at an unprecedented rate.

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The GCMs, imperfect though they may be, must be considered in aggregate to represent the best, current knowledge of atmospheric science. As such, a consistent prediction of global warming cannot be ignored. A survey of model output, combined with current and projected production of greenhouse gases results in a reasonable estimate of the magnitude of global warming to be in the neighborhood of 3°C by mid next century. This estimate is based on the assumption of a doubling in CO<sub>2</sub> by 2050, and as such is often referred to as the 2XCO<sub>2</sub> scenario. A global change in mean temperatures of this magnitude corresponds to that which occurred during the mid Pleistocene. Changes in Pleistocene climates resulted in substantial shifts in both plant and insect populations in the Rocky Mountain region of the U. S. (Elais, 1991). The major difference between global warming during the Pleistocene and the current situation is the projected rate of change, approximately 10 times that which occurred during the last interglacial (LaRoe, 1991). The disruptive potential is, therefore, much greater than that documented during the Pleistocene, perhaps orders of magnitude greater.

In view of the impacts that insects have on forest ecosystem structure and function, a legitimate question is: what are the impacts of global climate change on important insect species? A review of the limited literature on climate change effects on insect populations reveals the conventional wisdom is that pest problems will be exacerbated. This consensus results primarily from

analysis of the effects that temperature have on individual life history traits. Porter et al. (1991) provide a thoughtful review of these impacts. Of the ten attributes they considered, eight will likely enhance insect population success, and only two are ambiguous, with populations either positively or negatively affected. Review of the geological/fossil record tends to corroborate these conclusions. The rich diversity in insect species has apparently not resulted from a particularly high rate of speciation, but rather from an exceedingly low rate of extinction (Labandeira and Sepkoski, 1993). Extinction rates were relatively unaffected even during the late glacial and Holocene changes that were greater in magnitude (but not rate) than the 2XCO<sub>2</sub> scenario (Elias, 1991).

Additional insights may be gained by considering survival strategies of contemporary insect species to prevailing climate. For example, every year, many lepidopteran species in the Eastern U.S. migrate north far beyond the limits of typical overwintering success. In effect these insects "gamble" on the chance that unusually favorable weather conditions will allow expansion of the population into new habitats and/or expansion of geographic ranges. This survival strategy is an indication that insects routinely withstand the loss of significant biomass without suffering adverse evolutionary consequences. In the evolutionary game, insects often gamble on variation in weather events, and they often win.

In the few computer simulation studies that have been performed

with insect models, global warming has generally resulted in improved performance of the insect populations at the expense of the plant resource. Simulation studies performed by Stinner et al. (1989) indicated increased problems with potato leafhopper, black cutworm, green cloverworm, and corn earworm when various global warming scenarios were simulated for the mid-western agricultural region of the U.S. Finally, as an example by counter-example, in our work with mountain pine beetle, population decline, including collapse of outbreaks, have been attributed to unusually cold weather (e.g. Safranyik, 1978). Conversely, at least to our knowledge, reports of similar occurrences due to unusually mild or warm weather have not been reported.

An inescapable conclusion, given the current evidence, is that conventional wisdom is correct. In general terms, global climate warming will result in exacerbated insect pest problems. This is not to say, however, that the effects of every current pest species will increase under global warming. There will be winners and there will be losers. After all, pest populations are limited in their Southern distribution as well as in their Northern distribution. Projections regarding a particular pest species need to be made on a case-by-case basis. For example, mountain pine beetle (MPB) populations (*Dendroctonus ponderosae* Hopkins), would benefit from global warming due to reduced winter mortality. Conversely, global warming may interfere with the maintaining of an appropriate seasonality for

this non-diapausing species. Addressing such species response to modification of a basic ecological driving variable such as climate is a complex issue. Difficulty in dealing with this issue is further compounded by the fact that direct evidence is lacking and system level experimental manipulation is prohibitively expensive. These constraints are exactly those cited for difficulty in dealing with the physical aspects of climate change, and the proposed response is also the same. Computer models and the techniques of system analysis can provide a cost-effective way to evaluate population level and/or ecosystem level responses in anticipation of future events. In the remainder of this presentation we will first describe in general terms the climatic adapted ecology of MPB and a computer model designed to represent important aspects of that ecology. Next we describe the important habitat component of mountain weather on MPB population performance and a landscape-level approach to modeling this critical driving variable. Finally, we describe a research application that uses these models to evaluate the potential of MPB outbreaks as an indication of forest health in high-elevation pine forests.

### Climate and Weather Effects

The MPB is economically the most important bark beetle in western North America (Wood, 1963; Gibson, 1988). Although a wide range of *Pinus* species are suitable hosts, MPB is economically most important in lodgepole (*Pinus contorta* Douglas var.

*latifolia* Engelmann) and ponderosa pine (*Pinus ponderosa* Laws) forests. These two species are among the most widely distributed conifers in western North America. Periodically, large landscapes become vulnerable to mountain pine beetle outbreaks. For example, between the years of 1979 to 1983, over 4 million acres per year in the western United States were infested, resulting in mortality of over 15 million trees each year (McGregor, 1985). Although MPB is a serious competitor with humans for valuable natural resources, it also has been a major component of western pine forests for millennia. Mountain pine beetle outbreaks are an important component of the mechanism that maintains disturbance regenerated species such as lodgepole pine (Flint, 1924; Evenden, 1943; Roe and Amman, 1970; Amman, 1977; Peterman 1978). In fact the role of natural disturbances as determinants of ecosystem scale and pattern over large forested landscapes is becoming generally recognized (Hobbs and Huenneke, 1992). Mountain pine beetle populations can therefore be legitimately considered as either a serious pest or a critical component of western forest ecosystems. The challenge is to build a sufficient knowledge base to differentiate between outbreaks which are a pathologic symptom of an unhealthy ecosystem from those that are an essential component of a healthy, functioning ecosystem. A mechanistic understanding of the role that climate and weather play in determining population success is essential to such a knowledge base.

The effects of climate and weather are among the most important determinants of MPB population success. These effects are expressed directly through critical population constraints such as winter mortality. Cold temperatures in the winter have accounted for the greatest identifiable source of mortality in life-table studies (Cole, 1974; 1975). Apparently, a relatively narrow phenological window of larval stages are cold hardy, and an intensive research effort is currently underway to determine the mechanistic basis underlying cold-hardiness (Bentz, in press). Weather and climate also have more subtle effects on MPB population dynamics. Timing, and particularly synchronous adult emergence, are crucial for successful attack by a small weak predator (MPB) on a large, dangerous prey (pine trees). The significant defense mechanisms of pine trees to MPB attack can only be overcome through a mass attack strategy that numerically overwhelms the tree's defense mechanisms.

From the previous two examples, it is apparent that any climatic change has the potential for significant impact on MPB populations, including the increased likelihood of large-scale outbreaks. It is also clear that the effects of climate change may be counterintuitive. For example, a warming climate would favor over-winter survival, but at the same time could have a disruptive effect on maintaining the appropriate seasonality required for coincident adult emergence. The relevant question is what are the specific impacts of various climate change scenarios on the

expression of population success and/or outbreak potential? As a initial step toward addressing this question, we have begun development of landscape level models that couple population dynamics with landscape expression of climate and weather.

### Mountain Pine Beetle Population Model (MPBMOD)

In order to address both the direct and the indirect effects of climate and weather on MPB populations, it is necessary to represent (1) the full population phenology from egg deposition through adult oviposition, (2) oviposition and recruitment, (3) likelihood of weather related mortality. In addition to these basic processes, addressing questions of climate change requires expression of population dynamics over the complex mountainous terrain that to a large degree determine the proximate weather experienced by the population.

### Phenology

Temperature dependent phenology is generally recognized as the basis for representing the life system of poikilothermic organisms in seasonal environments. This is particularly true for insects such as the MPB that lack a true diapause. An appropriate seasonality is apparently maintained entirely through the relationship between developmental rates and developmental thresholds (Bentz et al., 1991). Egg phenology is modeled by the relationships described in Logan and Amman (1986). Larval and pupal phenolo-

gy are represented by relationships from Bentz et al. (1991). Parameters defining these relationships are included in the original publications.

A function describing the temperature dependent development of pre-ovipositional (POP) adults was derived from experiments that were conducted in "phloem sandwiches" (as described in Bentz et al., 1991). Constant temperature experiments were conducted at 6 temperatures, ranging from 17.5° to 30°C. These data are summarized in the original publication. The developmental rate function for POP adults is interesting in that it is essentially temperature insensitive for all but the lowest temperatures. Although small sample size, particularly at higher temperatures, compromises this data set, inclusion of the POP stage is necessary for system continuity and integrity. Sensitivity analysis with a complete life cycle model should provide an indication of the adequacy of the current functional form.

### Oviposition.

Recruitment is a basic population process necessary for continuity of the species. The magnitude of recruitment sets the ultimate constraint on population growth potential, and as such, is a fundamental component of the outbreak process. Additionally, since the ovipositional period is the functionally important time in the adult life-stage, the function can be used to model adult phenology. The rate and duration of the ovipositional period is temperature dependent, and

therefore, weather driven. In addition to temperature dependency, oviposition is also age dependent. For this reason, oviposition was modeled as a three step process requiring two functions; the first describing cm of gallery produced as a function of temperature, and the second relating fecundity to cm of gallery produced.

Temperature dependency of recruitment was determined by computing cm of gallery produced as a function of temperature [ $g(T)$ ]. Data from Amman (1972) was used to construct such a function. In the original publication, a nonlinear function was fitted to data describing average inches of gallery produced per day as a function of temperature. Subsequently, we have used a modified exponential curve since the original function was not defined at temperatures below 7°C, and oviposition has been reported at lower temperatures (Reid, 1962). Parameters for the exponential function were determined by first generating values from the relationship in Amman (1972), assuming a lower temperature threshold of 2°C (Reid reported oviposition at 1.67°C) and then using these data for parameter estimation. This procedure resulted in

$$g(T) = 0.169(e^{0.0194T^{1.34}} - e^{-\tau}) \quad (1)$$

for  $T = (T_o - T_b)$ ;  $\tau = -T/0.8$ ;  $T_o$  = observed temperature; and  $T_b = 2.0$ . The functional form of eq. [1] is empirically motivated, and similar to a previous function used to model ecological data with lower temperature thresholds (Logan et al., 1979).

The relationship used to describe brood production as a function of cm gallery length was based on data contained in Amman and Bartos (1991), Table 1, Group II and III. Data from this table were converted to rates by dividing the raw data by 15.2 cm, the linear length of the "bark strips" described in the original publication. X-coordinates used for curve fitting were determined as the mid-points of the five bark strips. Therefore, the resulting function has dimension of brood per cm gallery. The functional form fitted was piece-wise linear given as,

$$\begin{aligned} b &= 0.984 + 0.00248c_m \quad \text{for } c_m < 33.1 \\ &= 1.66 - 0.018c_m \quad \text{for } c_m \geq 33.1 \end{aligned} \quad (2)$$

The intersection of the two phases occurs at 33.1 cm, which corresponds to the estimated maximum rate of brood production. The X-intercept for the declining phase is 92.2 cm. In other words, the productive life of the female is 92.2 cm of gallery production. In order to determine total, potential brood production, the piece-wise linear function was integrated from 0.0 to 92.2, resulting in maximum recruitment of 65.4. Since the dependent variable is brood produced, background egg mortality is included in this estimate.

Simulation of recruitment and aging for ovipositional adult cohorts proceeds in the following manner. Step 1: compute the inches of gallery constructed during one day ( $G$ ) as,

$$G = \frac{1}{24} \int_0^{24} g[T(t)]dt \approx \frac{1}{24} \sum_{t=1}^{24} g[T(t)]. \quad (3)$$

where  $T(t_i)$  is Temperature at time  $i$ . Step 2: compute the physiological age (the proportion of the life stage completed) accumulated during the  $i$ th time step as  $a_i = G/(92.2)$ , i.e. the proportion of the total potential gallery construction complete during the  $i$ th day. The physiological age at the end of the time step ( $A_i$ ) is then computed as,

$$A_i = a_i + A_{i-1}, \quad (4)$$

for  $A_0=0$ . The ovipositional life stage is completed for a cohort when  $A_i = 1$ . The aging function,  $A_i$ , corresponds to the typical integration of the developmental rate curve (e.g. see fig. 2 in Logan, 1988). Step 3: include age dependency of oviposition by integrating eq. [2] for the cm equivalent of the physiological age elapsed during the simulation time step, i.e.

$$E_i = \int_{92.2A_{i-1}}^{92.2A_i} b(c_m)dc_m. \quad (5)$$

This final integral results in brood produced ( $E_i$ ) by the cohort for the simulation time step. Total egg recruitment is simply computed as the sum over all cohorts.

## Mortality

Since long before Malthus, it was generally recognized that the biotic potential of any population far exceeded the earth's capacity to sustain that population (see Hutchinson, 1978 for an enlightened review). This basic principle of population ecology is the reason why so much of insect

ecological research has focused on attempts to identify the key mortality agents operating in targeted populations. Although winter temperatures account for the greatest, identifiable mortality in MPB populations (Cole, 1981), little research has been focused on understanding the mechanisms involved. The likelihood of survival during winter months, as well as spring and fall, is a complex process that depends on the interaction of several factors including the frequency, severity, and duration of exposure to cold temperatures, and the cold-hardening capacity of the life stages present. Yuill (1941), Wygant (1942), and Somme (1964) investigated cold tolerances for mountain pine beetle larvae, although these studies were not instar specific. Reid and Gates (1970) and Safranyik and Whitney (1985) observed low temperature tolerance of MPB eggs. Information from these studies tend to be general in nature, and detailed studies of the interactions between low temperature, seasonality, and phenology are lacking, although investigations in progress should provide an understanding of the mechanistic basis for these important processes (Bentz, in press).

Since information is not yet available for a mechanistic model of winter mortality, we incorporated expert opinion to develop a rule based approach to modeling winter mortality. The resultant rule base was then re-evaluated within the context of existing data for inconsistency. Expert opinion was on stage specific mortality rules independently derived from interviews with G. D. Amman, L. A. Rasmussen, and B. J. Bentz.

Combined expertise represents approximately 70 years of observational history in a wide variety of MPB habitats. The rule-based development procedure was to individually state simple mortality rules for each life-stage, and then jointly negotiate differences in the rules. The mortality rule consisted of a base temperature at which mortality would first begin to appear, and the temperature at which 100% mortality would occur. Each of these two extremes was based on the daily observed minimum temperature, and the level of mortality between these two end-points was assumed to be linear. The mortality rule-base is summarized in table 1.

## Model Formulation

The Pest Model Design System (PMDS; Logan, 1988) was used to develop a computer simulation of the MPB model described herein. PMDS uses a robust cohort-based approach to model phenology. In addition, the computer generated code produced by PMDS is flexible enough that recruitment and mortality rules were easily implemented. A distinct advantage to utilizing the PMDS system for development of phenology based models is the user-friendly front-end that is automatically included. This user interface allows options for running the model with different temperature regimes, convenient modification of model parameters, etc. Copies of the executable and source (C language) code for MPBMOD may be obtained from J.A.L.

**Table 1.—Mortality rules based on “best guesses” of experts.**

Life Stage	Temperature at which mortality begins	Temperature at which mortality is 100%
Egg	-18°C	-18°C
Larvae 1	-23°C	-29°C
Larvae 2	-23°C	-34°C
Larvae 3	-29°C	-40°C
Larvae 4	-29°C	-40°C
Pupae	-18°C	-34°C
PreOvipositional (POP) Adult	-23°C	-34°C
Adult	-23°C	-34°C

## Including the Spatial Complexity of Orographic Influences on Climate and Weather

Most population models to date do not explicitly include a spatial component. The reason for this is not a perceived lack of importance, but due to the difficulty in modeling spatial phenomena Liebhold (1994) identified spatial complexity as one of the new frontiers for insect and disease models in forest pest management. Unquestionably, MPB population dynamics are played out in an exceedingly complex topographic arena. Mountainous terrain profoundly impacts both climate and weather, and any attempt to evaluate the affect of climate change by necessity must deal with the confounding problem of spatial complexity introduced by orographic influences on climate.

The influences of mountains on weather, as it impacts MPB population processes, occurs at four levels of organization. First is the synoptic level. At this level of organization, global circulation and global cycles come into play, as do continental

super-regional processes such as position of the jet-stream, prevailing winds, and frontal systems. The spatial scale is large, global to super-regional, and the influence of the processes at work impinge more on mountain weather than do mountains on the processes, although mountain influences can extend for considerable depth into the upper atmosphere. Synoptic influences operate at the seasonal, decade or century temporal scale. The second level is regional, involving dynamically and thermally induced wind systems. At this level, we are primarily considering the orographic influence of mountains on synoptic processes. These include those that result from the orientation and magnitude of the mountains themselves. The spatial scale is regional and the temporal scale ranges from seasonal to daily. The third level of influence is meso-scale and primarily dependent on the effects of slope and aspect. The spatial scale is local, in the range of tens to hundreds of meters and the temporal scale is on the order of daily cycles. The final level of organization is micro-meteorological processes that operate within the tree.

The spatial scale of these processes is less than that of the bole and depends on exposure (N, S etc.), height of the bole, etc., and their temporal scale is less than 24 hours.

In our modeling efforts, we are not attempting the synoptic scale. Such problems are best left to the physical meteorologists and their GCMs. However, the three lower levels of organization, and in particular the last two, fall into the realm of biometeorology and are of immediate interest. Modeling the orographic influence on temperature patterns presents three distinct challenges. First is simply the measurement of weather variables in a harsh mountain environment. Second is the problem of projecting a point source of information over a complex topography. And finally, the problem of reducing the complexity of the landscape to a manageable level. We will discuss each of these challenges separately.

From perusal of a map showing United States National Weather Service (NWS) reporting stations, it becomes obvious that major blanks exist which correspond to the high mountain regions. Even in mountainous regions of the western United States, standard weather stations tend to be located in the valleys. The reason for this is simple, people don't, as a general rule, live in the high mountains. The severe conditions of high mountains are hard on both people and equipment. As a result of this inadequate spatial coverage, simple statistical approaches to landscape modeling, such as Kriging, are inadequate for representation of mountain weather. A Kriged surface would resemble an elevated Great Plains. The rich mountain surface

responsible for orographic influences would be lost. The situation with respect to monitoring mountain weather is changing largely because of increased interests in mountain recreation and advances in meteorological instrumentation. We now have the motivation, both economically and ecologically, to measure mountain weather combined with the instrumentation that is capable of withstanding the rigors of high elevation environments. For example, the United States Department of Agriculture Soil Conservation Service (SCS) has recently established a comprehensive network of high elevation weather stations in the western United States. This network is a godsend for people interested in mountain environments, and in particular for those interested in mountain weather. This system is highly complementary to the NWS network, and significantly increases our empirical data base on high altitude weather and climate. Additionally, the data base (SNOTEL) is maintained on-line and is made available to legitimate users through the SCS national computer system.

Although recent developments, like the SNOTEL network, have significantly enhanced our ability to monitor mountain weather, the challenge of effectively projecting this point data across the complex terrain of interest still remains. The solution to this challenge involves modeling the effects of terrain on temperature. Our basic approach is to combine readily available digital elevation models (DEM) with the empirical analysis of historical weather data. Once stand (level 3) daily maximum and minimum

temperatures (level 4) are predicted to actually drive the simulation model.

Phloem temperatures are modeled in three stages. First stand air temperatures are projected, based on known maximum and minimum air temperatures at one or more "base" locations. Projections incorporate elevation and horizontal differences between base measurement and projected locations. Aspect and slope effects are also incorporated, e.g., higher maxima for steep southern exposures and lower maxima for steep northern exposures. Second, phloem maxima and minima are modeled for "shade" (north) and "sun" (south) portions of the bole. Finally, hourly temperatures are interpolated from these maxima and minima from an existing model (Parton and Logan, 1981). The first step uses the model:

$$T_{\max_s} = T_{\max_b} + \Delta H \cdot Lx_m + Imax \cdot Ex_{s,m} \cdot \frac{\Delta T}{\Delta T_{95}} \quad (6a)$$

$$T_{\min_s} = T_{\min_b} + \Delta H \cdot Ln_m \quad (6b)$$

where  $T_{\max}$ ,  $T_{\min}$  are daily maximum and minimum temperature, the subscripts  $s$ ,  $b$ , and  $m$  indicate stand, base, and month,  $\Delta H$  is the difference between stand and base elevation,  $Lx_m$  and  $Ln_m$  are average monthly vertical lapse rates for maximum and minimum temperatures,  $Imax$  is maximum exposure-caused temperature increase,  $Ex_{s,m}$  is an exposure index computed from slope and aspect  $(RS - Rflat) / (Rmax - Rmin)$ , where  $R$  is calculated monthly average potential diffuse plus direct solar radiation integrated from minus one to plus

three hours of solar zenith assuming 21 km clear sky (Hottel, 1976) and adjusted for slope and aspect (Swift and Knoerr, 1973),  $\Delta T$  is daily  $T_{max_b} - T_{min_b}$ , and  $\Delta T_{95}$  is historical 95 percentile  $T_{max_b} - T_{min_b}$ . The last term added in calculating  $T_{max_s}$  adjusts for warming resulting from cloudiness (i.e. sunny or cloudy day). The differential warming of western and southwestern exposures can exert a significant influence on orographic generated weather patterns.

The microhabitat temperature were predicted from modeled site maxima and minima by:

$$TP_{max} = T_{max_s} + \Delta P_{max_{s,m}} \cdot \frac{\Delta T}{\Delta T_{95}} \quad (7)$$

where  $TP_{max}$  is south-side phloem maximum temperature,  $\Delta P_{max_{s,m}}$  is maximum temperature increase for the stand and month (values derived from Schmid *et al*, 1992), and the remaining terms are as previously defined. South side phloem temperature minima and north side maxima and minima were assumed to be the same as air temperature maxima and minima (Schmid *et al.*, 1992).

Even with an adequate model that allows temperature projection from one point in the landscape to another, the challenge of representing phenology over the continuous landscape still remains. A solution that simply uses a pixel-by-pixel simulation is not practical for computational reasons, particularly when this approach would also require running the simulation model on the same basis. The solution to this problem is provided through

Geographic Information Systems (GIS) interpretation of the landscape and subsequent classification into a manageable number of ecologically similar units. Classification begins by obtaining a Digital Elevation Model (DEM, available from the United States Department of Interior United States Geological Service) representation of the landscape in question. Classification rules are then devised based on slope, aspect, and elevation. In our experience, classification rules that divide aspect into 16 classes ( $22.5^\circ$  increments), slope into 10 classes (ranging from  $0^\circ$  to  $\geq 45^\circ$ ), and elevation increments of 100 m have provided sufficient ecological resolution. The classification rules are implemented through a GIS (we are currently using IDRISI, Eastman 1993). For a typically complex mountainous landscape (7.5 min Quad spatial scale), classification results in approximately 50 landscape units. Although these landscape units are spatially disjunct, model predictions from landscape units classified the same will be identical (i.e. a lower elevation north-east facing slope may be the same as a higher elevation south-west facing slope). Further, once a landscape sufficiently large to include essential ecological characteristics has been classified, then the number of units required becomes independent of spatial scale. Scale independence might appear to be a self-evident result of classification, but the computational implications are significant. For example, if we were to attempt running the simulation model on strictly a spatial scale, a landscape resolution of 30 m seems ecologically

reasonable. With this spatial resolution, landscape level simulation of a 7.5 min Quad would require running MPBMOD on the order of 200,000 times. Furthermore, an increase in spatial scale would result in a linear increase of the number of simulations required to capture the landscape. Although evaluation of various classification rules remain an active research interest, and results to date must be considered preliminary, coupling GIS analysis with simulation results in a computational savings of at least several orders of magnitude.

## Model Integration

Work with the objective of integrating MPBMOD with the landscape temperature model is currently in progress. Our goal is provide a flexible front-end that allows convenient projection of selected population attributes over complex, mountainous landscapes.

## Interesting Hypotheses Relating to Mountain Pine Beetle Ecology

The Mountain Pine Beetle project of the US-Forest Service was initiated during the early 1960's in response to the large volume of timber that was being lost to this pest at that time in the western United States. The early emphasis of the project was protection of these timber values, although the approach was always to understand the basic ecology of MPB as a basis for development of management strategies. More recently, in

response to shifting societal and US-Forest Service priorities, the research emphasis of the project has evolved from that of protection ecology to one of disturbance ecology. Although protection of short-term timber value remains of interest, perhaps even more important is attempting to understand the ecological role of MPB disturbance in western coniferous forests. In particular, disturbance frequency and intensity is a major determinant of subsequent forest ecosystem pattern, structure, and function. Disturbances and changes in disturbance patterns may also be a key symptom of forest health and an indicator of larger ecological issues such as global climate change. It is in the role of basic disturbance ecology that mountain pine beetle becomes of interest in high-elevation, 5-needle pine forests.

Mountain pine beetle is a potentially important component of sensitive, high elevation pine systems, such as whitebark pine (WBP) forests. In contrast to the dynamics exhibited in lodgepole pine (LPP), MPB populations in WBP typically operate as a fugitive species. Due to the high elevation climate characteristics of WBP ecosystems, MPB populations are typically semivoltine and asynchronous (Safranyik, 1978). Populations of MPB in WBP, therefore, do not exhibit the predictable (Schmidt, 1989) cycle of beetle outbreaks and fire typical of lodgepole systems. Adverse effects of severe climate on population performance are primarily responsible for maintaining mountain pine beetle populations in a sub-outbreak phase in high elevation forests (Amman et al., 1977). Climate

effects are expressed in several related ways. Heat accumulation is not sufficient for completion of the typical univoltine life cycle and, as a result, populations are semivoltine. Stretching the life cycle over 2 years results in severe mortality consequences. Only a relatively narrow phenological window of life stages are cold resistant (larval instars three and four) and those life stages older or younger should suffer extreme mortality. In addition to mortality, the two year life cycle slows the insects physiological clock with respect to the chronological clock. As a result, critical life history events are prolonged and events that are synchronous in univoltine population would be temporally dispersed in a semivoltine population. Temporal dispersion could result in disastrous consequences for a species utilizing a mass-attack strategy to overcome host resistance. In this view, self-sustaining outbreaks of MPB in WBP would be unlikely and tree mortality from MPB should be temporally sporadic and spatially diffuse, with only the occasional weakened tree taken out. At least two exceptions to this generalization are possible. First, prolonged periods of unusually warm temperatures might allow population release and subsequent build-up of MPB populations within the WBP stand. The potential for climatic release of the population is particularly problematic given global warming scenarios. The second possibility results from movement of substantial numbers of MPB into WBP stands from adjacent LPP stands undergoing an outbreak. Such occurrences have been documented in forests

with a contiguous intergradation of LPP into WBP (Bartos and Gibson, 1990).

The high elevation 5-needle pine forest ecosystems of the western United States are unquestionably of high intrinsic and esthetic value. They are some of the oldest organisms in the interior west of the U.S., and as a consequence contain a lengthy biological record of climatic influence on ecological systems. Ecologists are becoming increasingly aware of the connectedness of ecosystems, and high elevation 5-needle pine ecosystems are no exception. For example, WBP seeds comprise an important component in grizzly bear diets during the critical time they are preparing for hibernation. Interestingly enough, conflicts between humans and bears increases significantly during years of poor WBP seed production (Mattson and Jonkel, 1990). High elevation ecosystems can be thought of as existing on the extremes. These type of systems, those that maintain themselves under consistently adverse or harsh conditions, are typically thought of as prime candidates for indicators of environmental change (Danks, 1992). With respect to the role that high elevation forests might play as "canaries of ecological peril," there is apparent evidence that high elevation forests are systems under siege. A good example are the so-called "ghost forests" of WBP found in various high elevation sites throughout the west, including the Sawtooth National Recreation Area (SNRA) near Stanley, Idaho. The name for these forests arise from the large number of standing dead trees,

which weather to a grey, ghost-like color. The real question of interest is; are the high mortality observations in the ghost forests an indication of pathologic change in the ecosystem, or are they simply a normal aspect of a healthy functioning ecosystem?

Motivated, at least in part, by the potential for an indicator of forest health, a US-Forest Service (Intermountain Research Station) project has been cooperatively funded with the Laboratory of Tree Ring Analysis at the University of Arizona (D. L. Perkins and T. W. Swetnam) to investigate mortality causes in the WBP ghost forests in the SNRA. In these investigations, it is becoming increasingly evident that significant, often catastrophic (over a period of 10 or less years) mortality, has resulted from MPB attack. This result is surprising because of the isolation (separation by non-host spruce-fir) of WBP from LPP. As previously noted, mortality could "spill-over" from an ongoing outbreak in an adjacent LPP stand (Bartos and Gibson, 1990), but the occurrence of outbreaks in ecologically isolated stands is enigmatic. Three possible hypotheses for this enigmatic observation seem possible. (1) Our understanding of weather effects on MPB population dynamics is seriously in error. (2) Unusually mild weather patterns over several years resulted in self-sustaining outbreaks. (3) Some, as yet unknown, transport mechanism resulted in import of sufficient beetles to cause catastrophic mortality.

The first hypothesis is currently a primary focus of the Mountain Pine Beetle Project of the USDA Forest Service Intermoun-

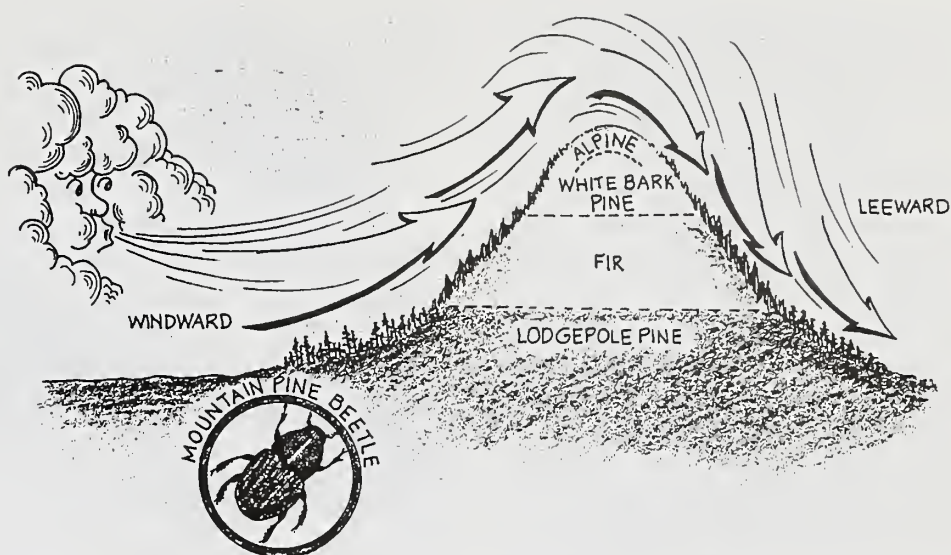


Figure 1.—Typical pattern of continental frontal storms. Prevailing winds from the west accelerate on the up-slope, windward exposures. A zone of turbulence and abrupt deceleration of the wind occurs on the leeward facing ridge tops. The decreased capacity for particle transport that accompanies the decelerating wind velocities are responsible for wind loading of snow during winter storm events. The obvious cornices that result are evidence of prevailing wind direction.

tain Research Station. Predictions from the previously described model are being rigorously validated in field experiments at a variety of geographic locations in the western United States (B. J. Bentz, in press). The second hypothesis is being tested by reconstruction of site-specific weather patterns using the previously described landscape model and historical records. This work is in progress for the MPB mortality events identified from tree-ring analysis to have occurred during the 1920's. Temperature model projections will be corroborated through tree-ring analysis of growth patterns for the time period of interest. To test the third hypothesis, we first need to identify a long-range transport mechanism. From the location of the ghost forests, and from prevailing orographic generated weather phenomena,

we have hypothesized a potential mechanism that is a consequence of the combined action of prevailing continental air-mass flow and thermally induced summer winds.

The first component of the hypothesized long-range transport mechanism became apparent during a late summer visit to one of the ghost forest sites. Even at the time of the visit (August) a sizable residual cornice remained above the site, indicating the extent of snow loading during winter storm events. The prominence of this cornice emphasized the direction of prevailing winds and suggested a beetle transport mechanism similar to the catchment and deposition that is responsible for snow wind-loading during a winter storm. The potential catchment area, far below the intervening band of non-host forest type, was

also apparent: a large valley-basin of monoculture LPP. Of course, while the mechanism suggested by the cornice is a winter phenomena, hardly suitable for transport of flying beetles, it is an indication of the predominant west-to-east continental air-mass flow (fig. 1).

A summer orographic weather phenomena that could serve to transport MPB from a spatially-separated outbreak in LPP up into high-elevation WBP habitat results from the summer "valley-winds" (Barry, 1992). In the western United States, almost all mountain ranges have a north-south orientation resulting in predominantly east and west facing aspects. The summer valley-winds result from thermal warming of east/west facing slopes and subsequent up-slope winds created by the rising warm air. In the mountainous United States, the typical situation is that gentle easterly breezes result as the morning sun begins to warm the east facing aspects. As the sun gains altitude and intensity, substantial warming occurs during the afternoon on the west facing aspects. In contrast to the gentle breezes characteristic of the morning easterly's, the afternoon westerly's are often powerful winds. As the thermally warmed air rises, it is compressed between the mountain ridge-line and the upper atmosphere resulting in increased wind velocity across the ridge top. Sudden deceleration on the lee side creates turbulent flow on the east facing slopes below the ridge line. The resulting turbulence is analogous to eddies formed as a river flows past a rock or other barrier. Beetles transported by westerly

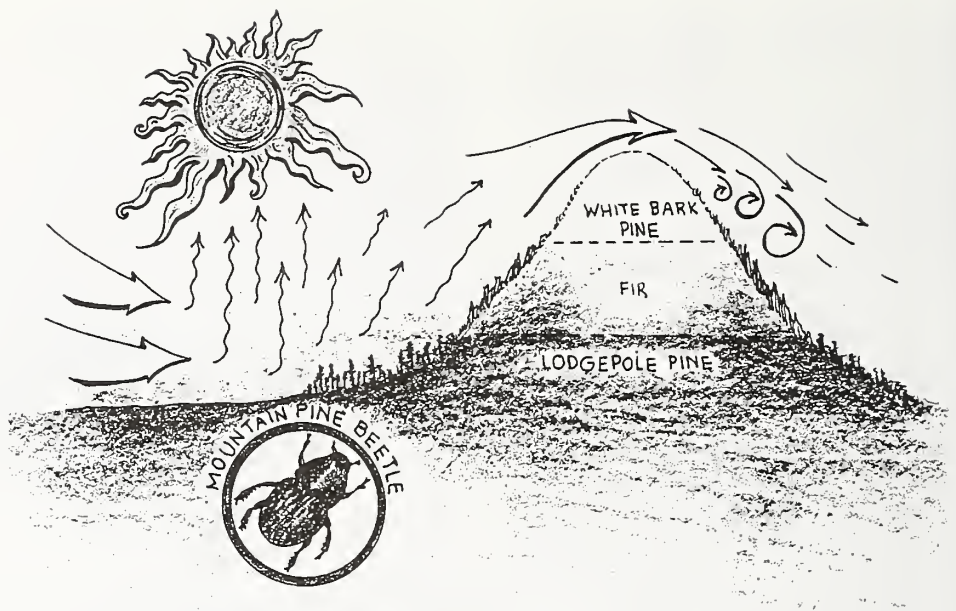


Figure 2.—Typically strong up-slope winds occur on summer afternoons as a result of thermal warming of west facing ridges. Velocities of these thermally generated winds are strong enough to establish standing eddies on the leeward (east facing) slopes. The predictable summer up-slope winds could act as a transport mechanism for mountain pine beetles in much the same way that winter storm patterns act as a snow transport and deposition mechanism. See text for further explanation.

valley winds would be "sucked" into the east-facing deposition zone by the turbulent flow, and once deposited, would tend to be held there by the resulting eddy lines (fig 2). These strong afternoon winds correspond temporally with the time of beetle emergence and flight.

The transport mechanism that we have described results in several predictions. The first, and most obvious is a MPB temporally coincident outbreak in an appropriate LPP stand. For the SNRA, "appropriate" means forests on the western aspect of east facing WBP stands. For example, MPB episodes in the Sawtooth mountains should be correlated with outbreaks in the Payett drainage, whereas those in the White Cloud mountains should be correlated with outbreaks in the Salmon river drainage. Lack of temporal correlation with an

appropriate outbreak would be evidence to falsify the long-range transport hypothesis. Conversely, there should be a lack of correlation with MPB outbreaks to the east of ghost forest sites. Attempts are currently underway to locate the appropriate historical records required to evaluate these spatial predictions. Another prediction would be lack of correlation between unusually mild weather and MPB caused mortality. This prediction can be tested by running MPBMOD for prevailing weather patterns reconstructed from historic records during the time of the MPB outbreaks. Lack of suitable high-elevation weather, as predicted by poor population performance from the model, during a mortality episode would tend to corroborate some transport mechanism. Finally we should be able to predict catchment and deposition zones

from a combination of topographic maps, forest cover types, and records of MPB outbreaks. These types of predictions can be automated through use of rule-based reasoning combined with GIS analysis of corresponding DEMs. Validity of these predictions can be ground-truthed as a measure of the predictive power of the hypotheses. The main point is, hypotheses regarding the mechanism of catastrophic mortality events in WBP result in testable predictions.

Determining the relative plausibility of competing hypotheses for the high-elevation ghost forests is important for several reasons. The critical question is: Did the observed MPB mortality result from unusually warm weather conditions? If the answer to this question is "yes," then the observed mortality serves as a warning of potentially exacerbated impacts of climate change due to increased MPB activity. Conversely, if the ghost forest mortality resulted from long-range transport of beetles, then it may well be that such occurrences have been a part of the WBP ecosystem for millennia. If we are to use the occurrence of insect outbreaks as an indication of forest health, the ability to differentiating between pathologic aspects of the system from normal occurrences in a healthy, functioning ecosystems is essential. Monitoring the occurrence of pest outbreaks may be an important indicator of changing climate and deteriorating forest health, but only if we know enough to determine the probable causality of temporal outbreak patterns. A mechanistic understanding of the WBP ghost forests has wider implications than simply for the high-elevation forests of the interior west. WBP and LPP have

evolved very different life-history strategies that enable them to adapt to various disturbances. Understanding these adaptations will help us to more fully understand the role of disturbance in forest ecosystem structure and function, and to effectively formulate management strategies in the face of global warming or other modifications to natural disturbance regimes.

### Summary and Conclusions

In summary, the conventional wisdom that a warming climate will result in increased insect pest problems is probably true. This conclusion results from a variety of life history characteristics that allow insects to effectively adapt to rapidly changing conditions. The demonstrated resiliency of insect populations in face of previous climatic variation reinforces this conclusion. Although in general terms insect pest problems may be exacerbated, it is difficult to make insightful predictions for a particular insect species, there will be winners and there will be losers in a changing global climate. The potential consequences, however, warrant the effort required to make honest attempts at evaluating consequences of climate change for potentially important pest species. Aggressive bark beetles, such as the mountain pine beetle, have the potential to foreclose evolutionary options of sensitive species such as WBP through mortality that negates the strategy of a long lived species persisting until adverse conditions improve.

The potential role of insects (or insect damage) as biological indicators of environmental stress and forest health is generally recognized. Biological systems serve to integrate the total environment, and as such, they may respond to changes in the physical environment long before the change could be directly measured. This potential is particularly important in situations such as the global climate in which subtle signals are hidden by background noise. It is generally recognized that the most sensitive indicators of ecosystem health are those components of the system that exist under conditions of chronic stress. Alteration in historical disturbance regimes with respect to intensity, duration, or magnitude in these conditions may be an efficient early warning of more widespread impacts in the future. The whole issue of forest health monitoring revolves around these concepts. The challenge is: Discriminating between ecological disturbance that is a pathologic symptom of an unhealthy ecosystem from those situations in which disturbance is a natural manifestation of a healthy, functioning ecosystem. The role of mathematical models can aid substantially in this discriminatory process, but only if they include validated representations of key ecological processes.

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# Development of a High Resolution Climatic Data Set for the Northern Rockies<sup>1</sup>

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**Abstract.**—Regional assessments of climate change effects on ecological systems require climate scenarios with detailed spatial information. Work with nesting mesoscale climate models under Global Circulation Models has shown some success down to the 50-km scale. Examination of 50-km resolution topography suggests that an even finer scale may be necessary to represent the complexity of climate distributions in the Northern Rocky Mountain region. A method for developing and testing climate scenarios developed for the 50-km and 10-km scale is outlined. A preliminary validation of results from the 50-km model against surface observations shows reasonable agreement for temperature. Precipitation is overpredicted, however. The validation also demonstrates that with 50-km resolution, climatically important topographic features are lost.

## Introduction

The need for spatially detailed climate scenarios in regions of complex terrain is well recognized. The great diversity in local climates present in the complex terrain of the Northern Rocky Mountains is a key to the vegetative diversity found there. If we are to understand how a global temperature shift and rainfall change will affect that vegetative diversity, we must be able to represent the spatial distribution of climatic variables over the region with climate change scenarios.

Monserud et al. (1993a) showed that most of the predicted changes in vegetation due to potential global climate change will be concentrated in the sub-boreal/temperate forest ecotone

regions because most of the warming is expected to occur in temperate and boreal regions. The Northern Rocky Mountains are within this region of greatest warming, and if the sub-boreal/temperate forest ecotone is sensitive to climate change, then the sub-alpine/montane ecotone should be similarly sensitive. Where topography and elevation differences create the ecotones, plant species have the opportunity to migrate over the warming period because distances over which climate differences exist are much shorter than for the sub-boreal/temperate forest ecotone.

Several techniques have been used to develop detailed climate change scenarios (Giorgi and Mearns 1991). Paleoclimatic analogues use information about how a locality adjusted to past climates to predict its future under a changed climate. The most promising analogues appear to have biases toward greater precipitation than global circulation model (GCM) predictions for increased CO<sub>2</sub> concentrations (Monserud et al. 1993b). Semi-

empirical approaches use empirical relationships for detailed climate developed with existing station information and overlay these relationships onto GCM predictions for double carbon dioxide (2XCO<sub>2</sub>) climates. The potential problem for these approaches is that relationships valid for the existing climate may change as the climate changes. The most promising approach appears to be climate modeling with explicit accounting for mesoscale forcings.

Marinucci and Giorgi (1992) demonstrated that using a limited area model (LAM) with 70 km resolution over Europe provided much more detail on the effects of climate change than the driving GCM. The Western United States is another frequently cited area where such an approach can be an improvement over GCM simulations (Giorgi et al. 1993a). At GCM resolutions, the Sierra and Cascade ranges are not represented, and the rain-shadow of those ranges, an important component to the ecology of the downwind areas, is not represent-

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ed. With 50-km resolution topography, the Cascades and Sierras can be seen (fig. 1).

A closer look at the 50-km topography reveals that several locally significant topographic features are missing from parts of the Western United States. One glaring omission is the Olympic Mountains of Northwest Washington, which play a key role in regional climate and ecology. Another omission can be found in the Northern Rocky Mountain Region. A comparison of figures 1 and 2 shows that where the 50-km digital elevation model (DEM) represents Northern Idaho and Western Montana as a broad concave rising slope from west to east, the 10-km DEM includes internal features such as the Bitterroot divide between Idaho and Montana, across which there are large climatic and ecological differences.

Climate scenarios available for assessment of global climate change effects in the Interior West have 50 km or more between grid points. Gridding at this scale smoothes the topographical representation of the region, and much of the climatic detail created by complex topographic forcing is not represented. Results from previous uses of Limited Area Models to improve resolution along with the comparison of topographic representations suggest that a 10-km LAM run over the Northern Rocky

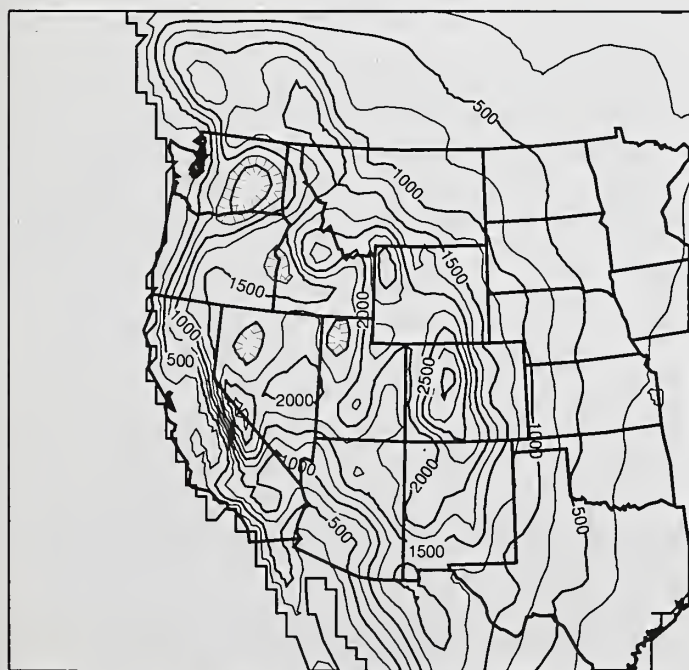


Figure 1.—Topographic map of western United States using 50-km Digital Elevation Model. (250-m contour interval.)

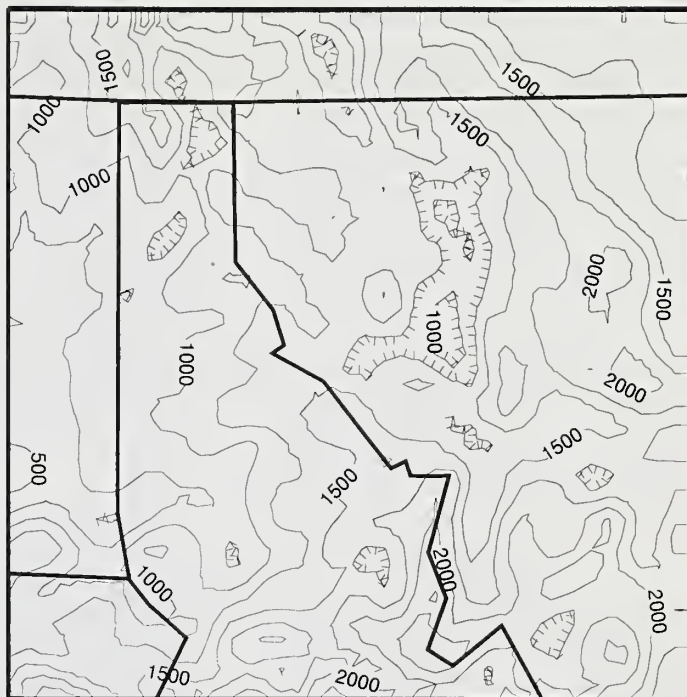


Figure 2.—Topographic map of northern Idaho and western Montana using 10-km Digital Elevation Model. (250-m contour interval.)

region would provide improved information on the distribution of surface climatic information over the area.

Testing the validity of this hypothesis can be done by comparing simulated climate detail for a topographically complex region for some period of record to surface weather observations for that period of record. After the validity of the model is established, comparisons can be made between change predicted by larger scale models and change predicted by the small scale model. Results of this study can be used to evaluate how well scenarios developed at the 50-60 km scale for global warming can describe the effects of global warming in comparison to scenarios developed at the 10 km scale.

The study is being conducted in two phases. The first phase is validation of the nested LAM runs for the period December 1978 to June 1992. The second is comparison of baseline and 2XCO<sub>2</sub> runs at the GCM, 50-km, and 10-km scales. The approach being taken in this study is to nest the 10-km LAM run over the Northern Rocky Mountains under a 50-km LAM run over the Western United States, which is in turn nested below a GCM scale grid. For the validation, the 10-km run is being run with boundary conditions prepared by the European Center for Medium Range Weather Forecasting (ECMWF) at

T42 scale. Results from the ECHAM4 model baseline and 2XCO<sub>2</sub> runs at Max Planck Institute will provide the GCM scale (T106) input to the 50-km model for examination of climate change. A 20-km LAM nested under ECHAM4 has recently been run over Europe (Christensen et al. 1995).

To date, a portion of the 50-km run under the ECMWF data set has been completed. This paper discusses preliminary validation of the 50-km run.

## Methods

The mesoscale models used in this study are the RegCM2 and RegCM2/HR models. RegCM2 is the MM4 climate model with some convective precipitation and radiation modeling improvements attached to a land surface model and tuned to 50-km resolution (Giorgi et al. 1993b, Giorgi et al. 1993c). RegCM2/HR is essen-

tially the same model, but tuned to 10-km resolution. The nesting of these models is discussed by Bingham et al. (1995). RegCM2/HR will be run over a rectangular area with the U.S.-Canada Boundary on the North; Grangeville, Idaho on the south; Glacier National Park on the east; and Spokane, Washington on the west. This general region was the focus of the validation of the 50-km model presented in this paper.

For the validation, we selected a 250-km by 250-km area over the Northern Rockies containing 25 50-km grid cells (fig. 3). Within this area, 39 Weather Service Co-op and Snotel weather stations with reasonable records for the January, 1981-December, 1983 period were identified. This period was selected because it is the longest unbroken period of record assembled from the 50-km model outputs to date.

Monthly maximum and minimum temperatures and monthly total precipitation were selected for examination. Extreme temperatures are the most difficult to model, and more important for ecological modeling than average temperatures. Precipitation is one of the most difficult parameters for the models to simulate, and is a key parameter for ecological modeling.

The parameters were averaged across all stations and all grid cells and plotted as a time series of average model values and average observed values. This approach is similar to that used in other validations of climate models (Giorgi et al. 1993a). Additionally, values from the 4 corner cells and the middle cell were compared to the average of the stations within each of the 4 corner cells and the middle cell (fig. 3).

## Results

Regionally averaged monthly maximum and minimum temperatures agreed reasonably well for the period (fig. 4). The model surface elevations are generally higher than the elevation of the weather stations (fig. 5), explaining the slight cold bias of the model. Small and sometimes negative temperature lapse rates are sometimes found for cold temperatures, but large temperature lapse rates are often observed during maximum temperatures. Using a blanket 8.25 degrees F per 1000 ft (15 C/km) lapse rate, the maximum temperatures for each station were adjusted to the model surface elevation with good results (fig. 6), demonstrating that the temperature departures are small enough to be accounted for by elevation. The lapse rates calculated by the model can be used for more detailed validations. The results are nearly identical for the five cell analyses.

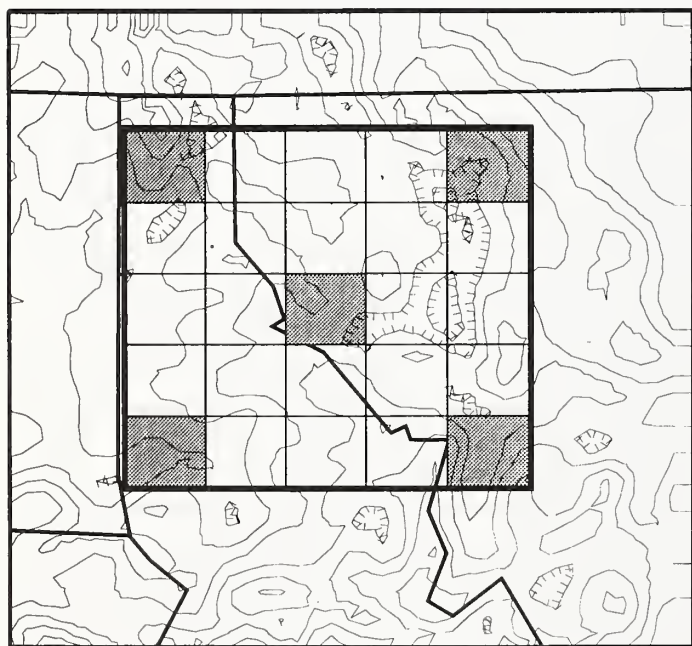


Figure 3.—250-km by 250-km area used for validation analysis. The five 50-km by 50-km cells used in the individual cell validation are shaded.

The regionally averaged monthly precipitation depths show that the model overestimates precipitation (fig. 4). The bias does not show the seasonal pattern reported by Giorgi et al. (1993a), suggesting that the improvements in convective precipitation schemes are effective. For the three year period, the model overestimated by 28 inches with an observed average of 93 inches for an approximate 30% over-prediction on the average for the period. The elevation bias of the weather stations compared to the 50-km model surface is the most likely reason for the discrepancy. Another possible reason may be that the modeled elevation of the Cascades is too low, allowing more moisture to pass through to the Rockies.

Examination of daily precipitation values shows that the model tends to simulate precipitation on more days than precipitation is actually observed. The overestimation seems to be caused more by a drizzling effect than a few extreme events. None of the numerical point storms reported by Giorgi et al. (1993) appeared in this data set.

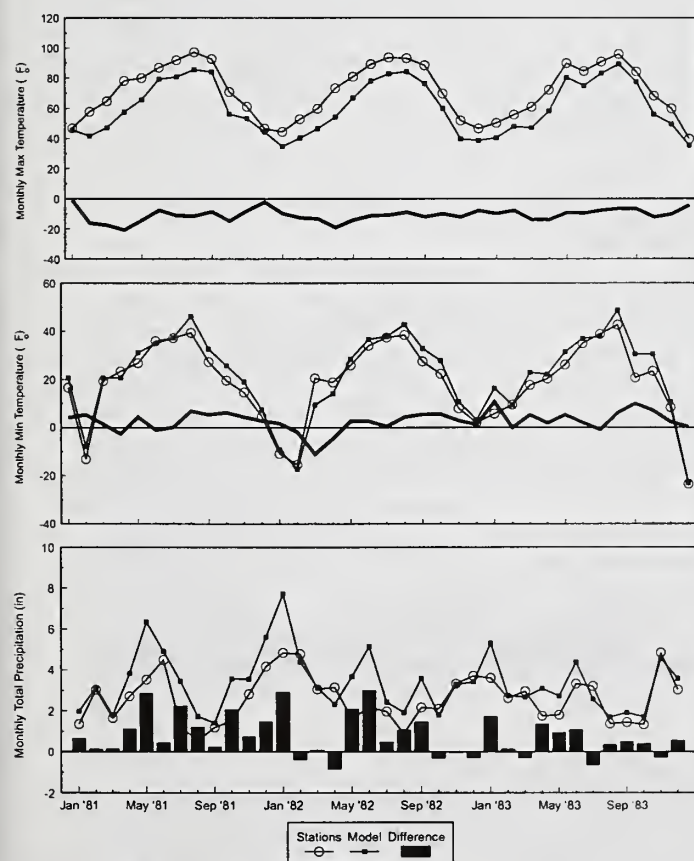


Figure 4.—Regionally averaged monthly maximum temperature, monthly minimum temperature, and monthly total precipitation.

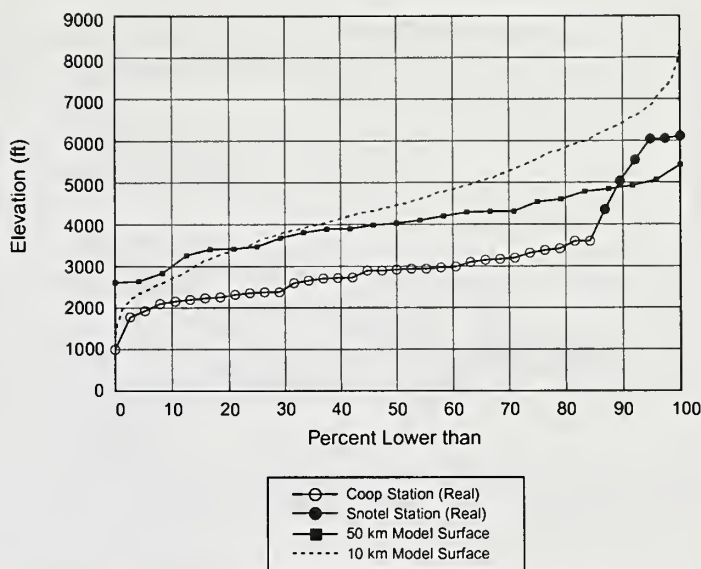


Figure 5.—Hypsometric relationships for stations and model surfaces.

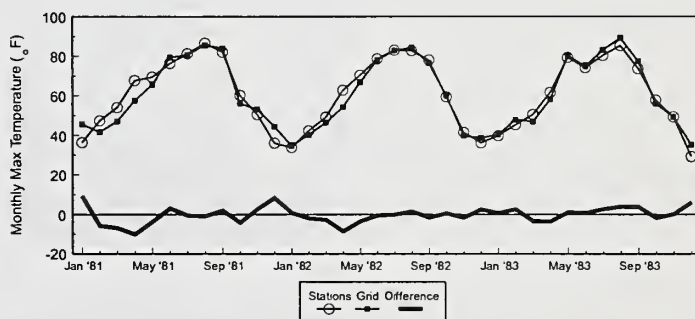


Figure 6.—Regionally averaged monthly maximum temperature with station data adjusted to the elevation of the model surface.

Examining the precipitation series for the 5 individual cells gives some insights about the biases found. For four of the five cells, the bias was similar to that for the average of all cells (fig. 7). However, in the lower right cell, the precipitation was consistently overpredicted with an error of 121% for the three year period. All of the stations in that cell are located in the Bitterroot Valley, in the rainshadow of the Bitterroot Divide. This valley does not exist in the 50-km resolution terrain. This discrepancy partially explains the overprediction for the average and suggests that better results may be obtained with 10-km resolution topography.

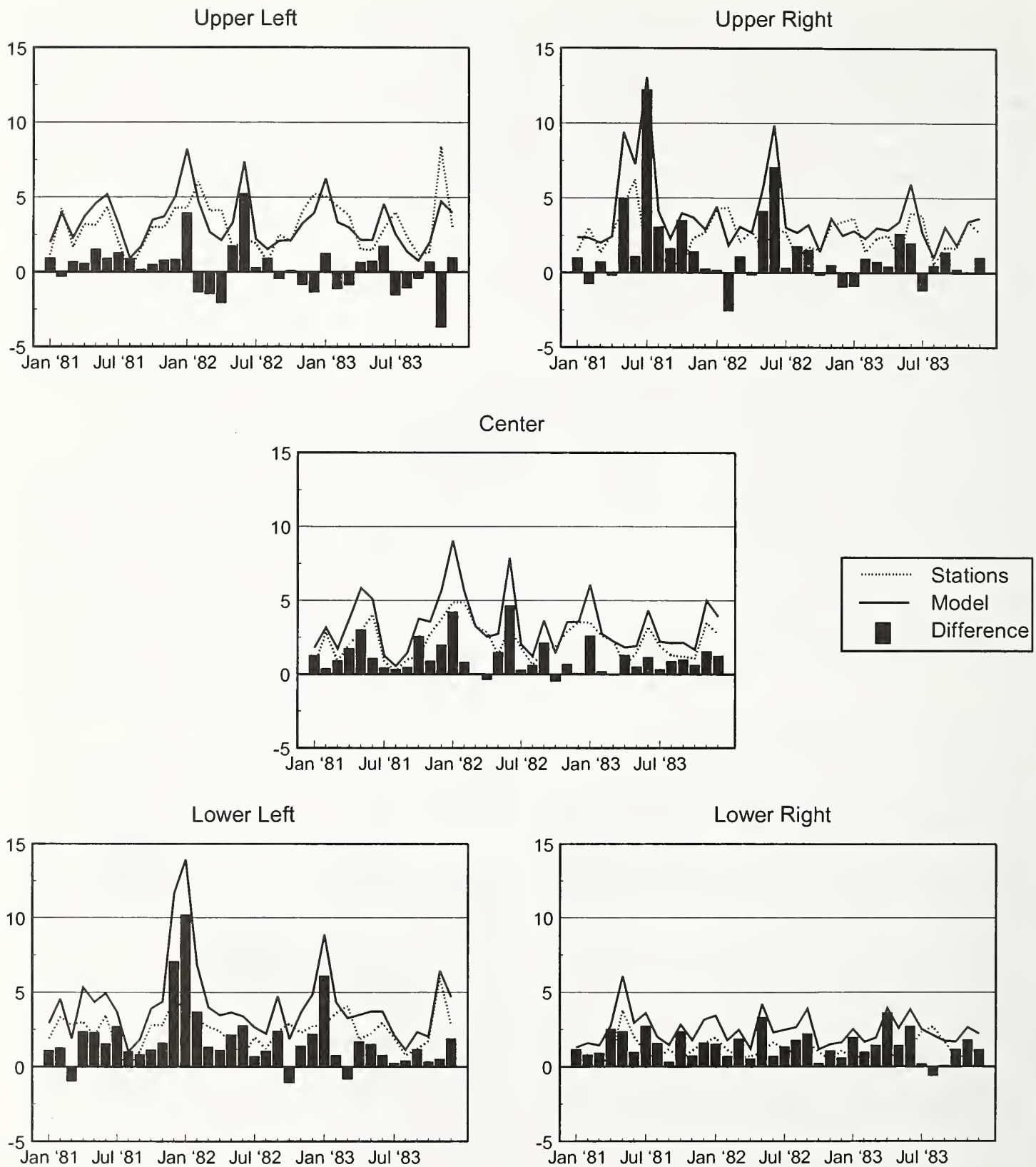


Figure 7.—Total monthly precipitation for the stations and the model surface at each of the four corner cells and the center cell of the analysis area.

## Conclusions

Strong conclusions would be premature with this analysis because only a few parameters were examined and only a portion of the available information was used. This brief analysis does provide some valuable information, however. The model appears to simulate temperatures well, but precipitation is overestimated. This information will serve to direct further investigations into the nature and the causes of the differences.

## Acknowledgment

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# Gas Exchange Parameters Inferred from $\delta^{13}\text{C}$ of Conifer Annual Rings Throughout the 20th Century<sup>1</sup>

J. D. Marshall<sup>2</sup> and R. A. Monserud<sup>3</sup>

Controlled experiments suggest that a 50-60 ppm increase in the  $\text{CO}_2$  concentration of the atmosphere, which has occurred during the past century, should have influenced the photosynthetic gas exchange of plants. Yet few experiments have shown conclusive evidence of a such a change in the field. In this study the stable isotopes of carbon in plant tissue provided a means of inferring the proportional decrease in carbon dioxide concentration across the stomata, which is closely related to photosynthetic water-use efficiency. We analyzed the stable carbon isotope composition of tree rings laid down over the past 80 years to determine whether the proportional decrease in  $\text{CO}_2$  concentration across the stomata had increased. Dominant and codominant trees of western white pine (*Pinus monticola*), ponderosa pine

(*P. ponderosa*), and Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) growing at the Priest River Experimental Forest, in northern Idaho, were analyzed. To avoid confounding age and year, we compared the innermost rings of mature trees to trees of intermediate age and to saplings. The isotopic data were corrected for changes in isotopic composition and carbon dioxide concentration using published data from ice cores.

Analysis of variance showed that the proportional decrease in carbon dioxide concentration across the stomata became smaller during the 20th century in all three species. Similarly, the inferred carbon dioxide concentration within the leaves increased throughout the period in all species. Interestingly, the shifts in gas exchange were just sufficient to maintain a constant differential in carbon dioxide concentration across the stomata. We interpret these changes as homeostatic in that they would tend to maintain constant net photosynthetic rates, provided stomatal conductance were unchanged. These results contrast with the expectation that rising concentrations of atmospheric

carbon dioxide will increase photosynthetic rates; however, they are consistent with the suggestion that deficiencies of mineral nutrients such as nitrogen have served as negative feedbacks on the carbon dioxide effects.

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# Predicted Effects of Climate Change on Phytomass and Net Primary Productivity in Siberia<sup>1</sup>

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## Introduction

Significant global climate change induced by a buildup of greenhouse gases in the atmosphere is a possibility receiving serious scientific attention (Houghton et al., 1990; Adams et al., 1990). The Intergovernmental Panel on Climate Change (IPCC) concluded that a radiative effective doubling of the atmospheric CO<sub>2</sub> concentration would likely change the average global temperature by 1.5 to 4.5 °C after equilibrium conditions were reached (Houghton et al., 1990). Warming is projected to take only 50 to 100 years, and would be concentrated more at high lati-

tudes than low latitudes (Houghton et al., 1990). Expected warming has been estimated to result in a redistribution of vegetation over the globe, especially in the boreal and temperate zones (Emanuel et al., 1985; Leemans, 1989; Smith et al., 1992; Monserud et al., 1993b). An increasing number of studies have used global vegetation models to analyze C storage changes in the global biosphere under CO<sub>2</sub> doubling climate scenarios derived from general circulation models (GCM's) (Prentice and Fung, 1990; Smith et al., 1992; Solomon et al., 1993; Smith and Shugart, 1993; Melillo et al., 1993; Dixon et al., 1994). More detailed process-based carbon dynamic models have been developed to assess both the influence of CO<sub>2</sub> concentration and climatic change on global and regional patterns of NPP (net primary productivity) (Janecek et al., 1989; Running and Nemani, 1991; Melillo et al., 1993).

Terrestrial vegetation may affect warming by means of feedbacks directly through the heat balance with changed albe-

**Abstract.**—Under current climate, we estimate the total phytomass of Siberia to be 74.1±2.0 Pg. In all four climate change scenarios, the predicted phytomass stock of all colder, northern classes is reduced considerably. Forest-Steppe greatly expands with all GCM's. A notable feature of these increases is the large introduction of Temperate Forest-Steppe under climate change. Moderate warming associated with the OSU and GISS projections resulted in a 23%-26% increase in phytomass, respectively. Greater warming associated with the UKMO and GFDL projections resulted in a small 3%-7% increase in phytomass, respectively. Thus, the Siberian phytomass component is sensitive to the degree of climate change, even though all scenarios correspond to the same CO<sub>2</sub> doubling equilibrium.

do, and indirectly through a mass transfer of carbon into the atmosphere (Janecek et al., 1989; Apps et al., 1993). Because boreal forests store a large amount of carbon and are located in latitudes that are predicted to undergo the greatest warming, they will play a key role in future carbon fluxes (Kolchugina and Vinson, 1993). Directions of resulting fluxes are still unclear, however. Neilson (1993) indicates that with warmer and drier climates boreal forests with high C stores will likely decrease in extent because of strong invasion by grasslands. Greater frequency and severity of forest fires predicted for boreal forests under global warming would release considerable carbon into the atmosphere (Perry et al., 1991). Smith et al. (1992) estimated enlarged C pools in boreal forests because of increased forest productivity and expansion into the current Tundra zone. A more accurate estimation of carbon gain or loss in vegetation under future warming could correct CO<sub>2</sub> concentrations estimated from GCM's alone.

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Our goal is to evaluate changes in phytomass and NPP of the vegetation of Siberia under projected CO<sub>2</sub>-doubling climate change scenarios. Because we use climate change projections from different GCM's, we can assess phytomass sensitivity to different climate change scenarios. We couple a Siberian vegetation model (Tchebakova et al., 1994) with four CO<sub>2</sub>-doubling climate change scenarios varying in global warming predictions. As with Solomon (1986), our strategy is to study regional climate change effects by coupling climate change scenarios from GCM's with a regional vegetation model. Regional vegetation models afford much greater accuracy and resolution than global vegetation models for the same region. We derive phytomass estimates from the important compilation of Bazilevich (1986), supplemented by additional literature on Siberian forests. We assume that all changes in phytomass are a result of the redistribution of vegetation zones. Because the Siberian vegetation model is an equilibrium model, we do not consider dynamic aspects of the carbon cycle, such as transient changes in vegetation redistribution and possible changes in phytomass density. We use forested percentages for each vegetation class from forest inventory summaries, which reflect the current levels of land use and disturbances. We focus on phytomass, and do not attempt to evaluate possible effects of climate change on soils and the enormous amount of carbon stored in peat bogs.

## Methods

### The Siberian Vegetation Model

The Siberian vegetation model (Tchebakova et al., 1994) is an equilibrium model based on bioclimatological considerations. It simulates the major vegetation classes (biome subdivisions) of Siberia from three climatic indices: growing degree-days (base 5 °C), dryness index, and continental index. Because these indices reflect requirements of plants for warmth, drought resistance, and cold tolerance, they define the main features of vegetation zones (biomes) and their subdivisions. Climatic inputs (monthly mean temperature, precipitation, vapor pressure, cloudiness, and albedo) are obtained from a global climatic database, supplemented by additional weather stations in Siberia; resolution is 0.5° longitude by 0.5° latitude. Because this model is a static equilibrium model, it can only predict the types of vegetation that are suited to the climate of a locality, not the vegetation that will actually be there.

Tchebakova et al. (1994) examined the performance of the model by comparing predictions with the Landscape map of the USSR (Isachenko, 1988), which was not used for model development. Predicted vegetation generally matches well with mapped vegetation. The general locations of all vegetation zones are predicted correctly. Kappa statistics (Monserud and Leemans, 1992) show good agreement at all scales of comparison (Tchebakova et al., 1994).

## Climatic Data

We used an improved version of the IIASA Climate Database (Leemans and Cramer, 1991) containing a global network of temperature, precipitation, and cloudiness. Humidity (or vapor pressure) was taken primarily from climatic reference books for the former Soviet Union (Anonymous, 1964-1970). Data from about 1200 weather stations in Siberia were used to interpolate precipitation on a 0.5° grid, and about 800 to 900 stations for interpolation of temperature, humidity, and cloudiness. Albedo (necessary to calculate Budyko's dryness index) was taken from Matthews' (1983) digitized albedo maps for the continents. This climatic data became input to the Siberian Vegetation model, which predicted a vegetation class for each half-degree latitude by half-degree longitude grid cell.

We used climate change projections corresponding to a doubling of CO<sub>2</sub> from the following four GCM's: GFDL, Geophysical Fluid Dynamics Laboratory of NOAA at Princeton (Wetherald and Manabe, 1986; Manabe and Wetherald, 1987); GISS, Goddard Institute for Space Studies of NASA at Columbia University (Hansen et al., 1983); OSU, Oregon State University at Corvallis (Schlesinger and Zhao, 1989); and UKMO, United Kingdom Meteorological Office (Mitchell, 1983; Wilson and Mitchell, 1987). Based on predictions of vegetation change from two global vegetation models and the Siberian vegetation model used here, the GISS and OSU scenarios indicated more moderate climate change than did the GFDL or UKMO

scenarios, which predicted the greatest change (Monserud and Leemans, 1992; Monserud et al., 1993a, 1993b).

## Phytomass and NPP estimation

We rely on the literature to obtain estimates of phytomass (above- and below-ground per unit area, including all forest stories and surface layers). Our main sources are the major compilations by Bazilevich (1986, 1993) and Bazilevich et al. (1986), which summarize the phytomass results for the former USSR compiled from more than 500 publications describing more than 2500 research plots. We used published data from 500 of these plots for Siberia to calculate mean phytomass (and standard deviation) for each vegetation class.

## Results

Under current climate, we estimate the total phytomass of Siberia to be  $4.1 \pm 2.0$  Pg (table 1). In all four climate change scenarios, the predicted phytomass stock of all colder, northern classes is reduced considerably (viz.,

Tundra, Forest-Tundra, Northern Taiga, and Middle Taiga). Forest-Steppe greatly expands with all GCM's. A notable feature of these increases is the large introduction of Temperate Forest-Steppe under climate change; with current climate, this vegetation class is nearly non-existent in Siberia. Moderate warming associated with the OSU (Oregon State Univ.) and GISS (Goddard Institute for Space Studies) projections resulted in an 23-26% increase in phytomass (to  $91.3 \pm 2.1$  Pg and  $93.6 \pm 2.4$  Pg, respectively). Greater warming associated with the UKMO (United Kingdom Meteorological Office) and GFDL (General Fluid Dynamics Laboratory) projections resulted in a 3-7% increase in phytomass (to  $76.6 \pm 1.3$  Pg and  $79.6 \pm 1.2$  Pg, respectively). Thus, the Siberian phytomass component is sensitive to the degree of climate change, even though all scenarios correspond to the same CO<sub>2</sub> doubling equilibrium.

Total Siberian NPP increases under all four climate change scenarios (table 1). However, the rate of the increase varies in the two groups of scenarios. The most significant change occurs

with the warmer GFDL-UKMO scenarios, with NPP increasing 60%. Even though NPP of Tundra, Forest-Tundra, Taiga, and Semidesert will decrease because of a reduction in area, the loss will be compensated for by a large increase in the NPP of Forest-Steppe (three to seven times greater in comparison to current climate), Subtaiga (two times greater), and Steppe. This large increase is a result of an expansion of the area of these biomes. The herbaceous vegetation dominating Steppe and Forest-Steppe has a higher NPP than arboreal vegetation.

## Discussion

Results indicate enormous potential change in the spatial distribution of vegetation in Siberia because of climate change (CO<sub>2</sub>-doubling). Although the GFDL and UKMO scenarios predict more extreme warming than the GISS and OSU scenarios, all four GCM's predict large reductions in the area of Tundra and Forest-Tundra, reductions and northern shifts in the various classes of Taiga, and reductions in

Table 1.—Phytomass and net primary productivity (NPP) of Siberian biomes under current climate and climate change.

No.	Biome	Phytomass (Pg)					NPP (Pg/yr)				
		Current climate	GISS	OSU	GFDL	UKMO	Current climate	GISS	OSU	GFDL	UKMO
1	Tundra	2.5	0.4	0.7	0.3	0.3	0.48	0.07	0.14	0.05	0.07
2	Forest-Tundra	3.6	1.6	1.6	0.7	0.6	0.53	0.23	0.23	0.10	0.08
3	Taiga (and Subtaiga)	62.6	73.2	73.4	40.0	44.4	5.42	6.17	5.35	3.16	3.92
4	Forest-Steppe	3.7	14.2	15.7	32.3	31.8	1.15	3.69	3.68	8.14	8.35
5	Steppe	1.5	1.9	2.1	3.3	2.4	1.04	1.26	1.41	2.28	1.63
6	Semidesert and Desert	0.1	0.0	0.1	0.0	0.0	0.07	0.01	0.06	0.01	0.02
	Total	74.1	91.3	93.6	76.6	79.6	8.69	11.44	10.86	13.74	14.07

Steppe. Large increases in area are predicted for the Temperate Forest-Steppe and Temperate Steppe vegetation zones, and for Forest-Steppe and Subtaiga in the Boreal zone.

The resulting effect on total phytomass depends on the degree of warming. With moderate warming (OSU and GISS), phytomass is predicted to increase considerably. With greater warming (UKMO and GFDL), a smaller increase in phytomass is predicted. These conflicting results can largely be explained by the effect of warming on the future distribution of Taiga. Southern Taiga and especially Subtaiga will flourish under the moderate warming scenarios. In contrast, Taiga will shrink while Forest-Steppe and Steppe expand with the more extreme warming scenarios. Because Forest-Steppe and Steppe have considerably less average phytomass than Taiga, these offsetting effects result in only a small net change. Thus, for phytomass estimation, it matters greatly which GCM is being used to predict climate change.

The increase in the total NPP of Siberia under future warming occurs primarily because of the predicted expansion of herbaceous vegetation at the expense of arboreal vegetation. As a result, net annual carbon sequestration (i.e., net ecosystem productivity) should decrease, for most of the herbaceous plant mass is decomposed during the same year it has been formed. Trees, however, provide a long-term accumulation of carbon. Thus, carbon would be lost during the shift from arboreal to herbaceous vegetation, even though NPP would be increasing.

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# Analysis of Correlated Crown and Stem Characteristics in Three Conifer Species at the Priest River Experimental Forest<sup>1</sup>

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In the summer of 1994, 68 trees of western white pine, Douglas-fir and ponderosa pine were felled and sampled for analysis of the relations between stem and crown characteristics. The study was designed to provide measurements required to parameterize a biogeochemical process model, Forest-BGC, which will be used to reconstruct the past 80 years growth in the sampled stands on the Priest River Experimental Forest. We plan to compare model runs incorporating corrections for rising atmospheric CO<sub>2</sub> and observed increases in night-time temperature to runs without the corrections. The model depends on estimates of leaf area index (LAI) to predict components of the carbon budget, including stemwood production.

Leaf area estimates for each quarter of the crown will be

generated from the following equation:

$$\text{Leaf area} = \text{cqfw} * \text{sbdw/sbfbw} * \text{sndw/sbdw} * \text{sbsla} \quad (1)$$

where *cqfw* is crown quarter fresh weight, which was measured in the field immediately after felling; *sbfbw* is sample branch fresh weight, which was measured in the field on two randomly chosen branches from each crown quarter, *sbdw* is sample branch dry weight, which was measured on the sample branches oven-dried at 70°C; *sndw* is the dry weight of the needles plucked from each sample branch; and *sbsla* is the specific leaf area, or ratio of projected surface area to dry weight as determined by a laboratory video image analysis system, of a subsample of needles from each sampled branch.

Sapwood cross-sectional area (SWA) will be correlated with leaf area above that point, accounting for variation in ring width within the sapwood. SWA is being measured from cross-sections cut from the main bole at 1.3 m above the ground and at the base of each crown quarter. Ring widths are being measured in the sap-

wood of each cross-section to correct for possible variation. The areas are being determined by video image analysis of photographs of the cross-sections and ring widths were measured by hand.

Results available to date include analyses of green specific gravity of the bolewood and specific leaf areas of ponderosa pine. Specific gravity is necessary to convert the predictions of Forest-BGC, which are in kg of C per hectare per year, to the volume measurements traditional in forestry. Mean values were 0.47 (SE = 0.01) g cm<sup>-2</sup>, 0.41 (SE = 0.01) g cm<sup>-2</sup>, and 0.39 (SE = 0.01) g cm<sup>-2</sup> for Douglas-fir, ponderosa pine, and western white pine, respectively. These values are five to nine percent higher than those reported in textbooks for these species, and were observed to vary with growth rate. Specific leaf area of ponderosa pine averaged 24.9 (SE= 0.5) cm<sup>2</sup> g<sup>-1</sup>, 24.5 (SE= 0.5) cm<sup>2</sup> g<sup>-1</sup>, 26.1 (SE= 0.5) cm<sup>2</sup> g<sup>-1</sup>, and 25.2 (SE= 0.5), respectively for crown quarters from the uppermost to the lowermost; no significant differences were observed when the data were analyzed by a one-way analysis of variance (F=1.6, P>F = 0.19).

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# 245 Global Climate Change, Land Management, and Biosolids Application to Semiarid Grasslands<sup>1</sup>

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**Abstract.**—Global climate change combined with improper land management, including over-grazing, can lead to a severe reduction in plant cover and soil productivity. This process is especially common in arid and semiarid regions with sparse vegetation cover. New and innovative methods of land management are needed to restore and maintain these ecosystems in a productive and sustainable state. Research conducted in New Mexico on the Rio Puerco Resource Area and the Sevilleta National Wildlife Refuge has shown that biosolids (municipal sewage sludge) application to semiarid grasslands can increase soil nutrient availability, increase plant cover and productivity, and decrease surface runoff and soil erosion without harming environmental quality.

## Introduction

Over the past century, southwestern rangelands have experienced substantial changes in plant cover, density, and species composition (Dortignac and Hickey 1963; Buffington and Herbel 1965). Often, these changes have resulted in the conversion of grassland to shrubland, which decreased the forage value of the land and left it more susceptible to water and wind erosion (Grover and Musick 1990; Schlesinger et al. 1990). The net result of these changes was resource degradation (reversible) and/or desertification (irreversible). Although definitions of degradation and desertification vary, it has been estimated that in the United States alone, more than 225 million acres have experienced severe or very severe desertification (Sheridan 1981).

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Traditional range management theory would predict that these disturbed ecosystems would return to grassland if the disturbance was decreased or eliminated. Inherent in traditional theory is the belief that semiarid rangelands exist in an equilibrium with one stable state (climatic climax). However, practical application of this theory (removal of disturbance) has yielded little success in restoring or maintaining the productivity of many arid rangeland ecosystems around the world (Westoby et al. 1989; Ellis and Swift 1988; Johnson and Mayeux 1992).

One explanation of this phenomenon is the theory of multiple stable states (vegetation assemblages) in grassland plant communities, which does not assume equilibrium conditions (Westoby et al. 1989; Friedel 1991; Laycock 1991; George et al. 1992; Tausch et al. 1993). Stable states can be envisioned as being separated by thresholds of disturbance. The magnitude of the threshold is directly proportional to the stability of the vegetation assemblage. When disturbance (over-grazing, fire suppression, soil

erosion) forces the system across a threshold and a shrubland or woodland is established, it may become difficult to reestablish a functioning, stable grassland.

The forces of change in semiarid ecosystems are generally lumped into two categories, climatic variability and land management. Climatic variability includes both short-term and long-term variability. The land management practices thought to be most responsible for vegetation change are livestock grazing and fire suppression. There is much debate in the scientific literature as to the role of long-term global climate change in rangeland degradation. Separate studies that used climatic and vegetative data from the Jornada Experimental Range in southern New Mexico concluded that climate change was (Neilson 1986) and was not (Conley et al. 1992) a major factor in vegetation change in this region. However, most sources agree that the combined effects of short-term climatic fluctuation and improper land management are responsible for many of the problems associated with semiarid rangelands

today (Neilson 1986; Westoby et al. 1989; Grover and Musick 1990; Schlesinger et al. 1990; George et al. 1991; Milton et al. 1994). One way of visualizing the apparent synergistic effects of climate and land management on semiarid ecosystem stability is that climate change may have been responsible for altering the relative stability of alternate stable states and land management may have provided the force (disturbance) necessary to cross the stability threshold (Tausch et al. 1993).

It has been suggested that many southwestern semiarid grasslands are actually relicts that developed during a more mesic climate (Neilson 1986) and are present today because of stabilizing processes such as fire and "biological inertia" (Tausch et al. 1993). The presence of grasslands at the time of European settlement in the Southwest may have led to the erroneous conclusion that grassland was the climax for this area when, in actuality, it was one of several possible stable states. Regardless of the causes, the poor health of the nation's rangelands has become a national issue that demands a response from all parties responsible for their management (Joyce 1995). It will take a substantial investment in resources to reestablish productive, sustainable grasslands. Soil amendments such as biosolids, which supply plant nutrients and organic matter, may be an important part of a program to improve or reestablish grasslands under these environmental conditions. The specific objectives of our biosolids research program are to: (1) determine the effects of biosolids application on soils and vegetation in semiarid grassland

ecosystems, (2) determine how biosolids application influences infiltration and runoff of precipitation, (3) assess the fate of potential contaminants in the soils and vegetation, and (4) determine the potential value of biosolids application as a land management practice.

## Results and Discussion

### Biosolids Application to Semiarid Grasslands

Ultimately, the success of any restoration project is determined by the long-term vegetation response. The vegetation response in a water and nutrient limited system is dependent upon soil stability and water and nutrient availability. The results from two separate projects have shown that surface-application of biosolids (22.5, 45, and 90 Mg/ha, dry weight equivalent) to two semiarid grasslands significantly increased plant-available nitrogen and phosphorus, two of the most commonly-limiting plant nutrients (Fresquez et al. 1991; Loftin and Aguilar 1995; Loftin et al. 1995).

Vegetation response varied depending on the quantity and timing of precipitation after the biosolids application. In general, significant increases in vegetation cover and biomass were recorded when water was available, however, biosolids application can decrease species diversity and alter their relative abundance (Fresquez et al. 1990; Loftin and Aguilar 1994). This is not necessarily a problem, for example, a decrease in the abundance of broom snakeweed (*Gutierrezia*

*sarothrae*), an overgrazing indicator, was observed following sludge application in the Rio Puerco project.

Runoff of precipitation from natural storms and rainfall simulation experiments (1, 2, and 3 growing seasons after biosolids application) on the Sevilleta NWR was significantly reduced by a 45 Mg/ha surface application of biosolids (Aguilar et al. 1994; Loftin and Aguilar 1995). However, surface applications of biosolids (22 and 41 Mg/ha) did not significantly decrease runoff during rainfall simulations on a semiarid grassland in Colorado (Harris-Pierce et al. 1995). These differences were attributed to the time delay between biosolids application and rainfall simulation. Rainfall simulations occurred six months after biosolids application in the New Mexico study and two weeks after application in the Colorado study. It is possible that, at least initially, the hydrological effect of biosolids is increased by weathering and decomposition.

It is important to consider the potential for heavy metal contamination in any biosolids application. Although heavy metal loading rates for all biosolids applications were well below USEPA (1993) guidelines for agricultural applications, some significant increases were recorded. In the Rio Puerco project, significant increases in soil Cu and Zn were recorded after the first growing season (Fresquez et al. 1990), while significant increases in Cd, Cu, Pb, and Zn were recorded after nine growing seasons (Loftin et al. 1995). After five growing seasons soil Cu levels from the highest applica-

tion (90 Mg biosolids/hectare) were up to 29.78 mg/kg, which is considered to be potentially phytotoxic (Tiedemann and Lopez 1982) although no evidence of phytotoxicity was observed. In the Sevilleta project, an application of 45 Mg/ha produced significant increases in soil Cu, Pb, and Zn, but not Cd (Loftin and Aguilar 1995). Although significant increases in soil heavy metals were recorded in both projects, the peak concentrations in soils were so low, with the exception of Cu from the 90 Mg/ha application, that there should be no problem with heavy metal toxicity.

### Management Implications

The immediate response of grassland to biosolids application is dependent upon the short-term climatic patterns that control water availability. Just as climate and disturbance combine to force grasslands to shrublands, restoration practices would be more successful if they capitalized on favorable climate. This concept has been termed "adaptive land management" and has been discussed as one possible way to more effectively manage nonequilibrium rangelands (Westoby et al. 1989; Grover and Musick 1990; Dodd 1994; Milton et al. 1994). Whereas this form of management may have been nearly impossible in past years, today we have the ability to forecast broad-scale climate patterns with some accuracy. Land management personnel could take advantage of this predictive ability and schedule restoration programs accordingly.

Restoration with biosolids is a relatively short-term endeavor designed to stabilize soils and reestablish productivity in a disturbed ecosystem. Biosolids application (or any other restoration program) is too expensive and time consuming to be used as a "fertilizer application" to periodically boost declining forage yields. Therefore, the long-term sustainability of a restored ecosystem is dependent upon subsequent land management. A return to past management practices could lead back to pre-restoration conditions. Consequently, the next phase of our biosolids research program is designed to investigate the effects of management (grazing and/or prescribed fire) on the stability of restored areas.

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# Modeling the Effects of Climate Change on Fragmented, Linear Forest Systems in Mixed Agricultural Landscapes in the Great Plains<sup>1</sup>

David S. Guertin,<sup>2</sup> William E. Easterling,<sup>2</sup> and James R. Brandle<sup>3</sup>

The landscape of the Great Plains has changed considerably since the past century. What was formerly mainly prairie has mostly been converted to agriculture, particularly in the eastern Great Plains, where precipitation is the greatest (Griffith 1976, Langner and Flather 1994). As natural grasslands have been converted to crops, spaces between the intensely managed agricultural fields have become refuges for biological diversity. A significant portion of these spaces is wooded, either with shelterbelts or riparian forests (Schroeder 1986). Both of these types of forest are usually linear corridors. Both also have been increasing in prevalence, especially riparian forests in response to reduced stream flows due to irrigation, so that some riparian areas such as the Platte River today contain

considerably more trees than they did 100 years ago (Johnson 1994).

The overall landscape structure of the Great Plains is thus composed of large expanses of unforested land scattered with forest patches of various sizes and composition (Barker and Whitman 1988). Trees make up about 3% of the land area of the Great Plains (Griffith 1976). Although these forest patches are small relative to the entire landscape, they play important ecological and economic roles. Woodlands adjacent to agricultural land provide significant advantages to crop production (Kort 1988), and provide patches of relatively undisturbed habitat for animals. This includes the trees themselves, as well as scattered patches of untilled prairie vegetation adjacent to the trees.

The past several years have seen increasing attention to effects of climate change on ecological phenomena. These include implications for biological diversity, such as shifts in the geographical ranges of trees (e.g. Shugart 1984, Botkin 1993), and physiological challenges of dealing with a changing climate for both plants and animals

(Tracy 1992, Woodward 1992). Other studies have focused on economic impacts of climate change, such as effects on crop production in agricultural regions (e.g. Parry et al. 1988, Smith and Tirpak 1990, Easterling et al. 1993, Rosenzweig and Parry 1994). In the Great Plains, the economic implications of changes in agricultural production have received particular attention (e.g. Kaiser et al. 1992), but climate change may also have significant impacts on native plants and animals. Furthermore, anticipated adaptation strategies such as increased irrigation water use may amplify climate change impacts on them. Not only does the diversity of native species produce societal benefits by itself, such as economic or aesthetic value (Ehrlich and Wilson 1991), but it may also have importance for maintaining the stability of ecosystems, including agricultural ecosystems (Pimentel et al. 1992, Naeem et al. 1994). Thus the effects of climate change on biological diversity and agricultural production may be closely related. The Great Plains therefore has the capacity to foster research on not only each of these potential impacts separately, but also in the relationships between the two.

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Models to predict these effects in intensively managed agricultural systems have not received as much attention as have models for predominantly forested regions (e.g. Peters and Lovejoy 1992). In this study we hope to focus attention on the application of forest models to regions where trees make up a small but ecologically important portion of the total land area.

### Forest Models

Models of the responses of forests to potential climate change are numerous and have been reviewed by Shugart et al. (1992) and Malanson (1993). Most existing models have some significant shortcomings, however, when applied to a region with patchy distributions of trees such as the Great Plains. Forest gap models (e.g. Shugart 1984, Botkin 1993) (or community dynamics models, *sensu* Dale et al. 1985) show particular promise in being adapted to these fragmented landscapes, and our work is based on these models.

Community dynamics models are based on the establishment, growth, and death of individual trees on a plot small enough to be influenced by a single large tree (see reviews in Shugart et al. 1992 and Malanson 1993). Most are modifications of the original JABOWA (Botkin et al. 1972) and FORET (Shugart and West 1977) models. Effects of climate change are modeled by their direct effects on the performance on individual trees, with physiological detail based on empirical relationships rather than cellular mechanisms. Each tree on the plot grows at a

rate determined by a maximum growth rate that is reduced by environmental parameters (Botkin 1993). Temperature, light availability, soil water, and soil fertility all reduce the growth rate below the maximum unless they are at optimal levels. Direct effects of CO<sub>2</sub> on tree growth may also be represented, albeit simplistically (e.g. Prentice et al. 1993).

These individual effects result in changes in forest composition and structure on the modeled plot. Interactions among individual trees are represented mainly by competition for light, and stand-level effects are determined by the outcome of those competitive interactions. The detail in these models, while not as great as in more complex physiological models, provides insight into the processes underlying observed patterns of tree species distributions.

### The Seedscape Model

We are developing a community dynamics model called SEEDSCAPE, derived from the JABOWA-II model (Botkin 1993). It models an array of forested plots in a spatially explicit landscape, in part using modifications developed for the SEEDFLO model (Hanson et al. 1990). This allows us to vary environmental parameters among 10 x 10 m plots, instead of assuming constant parameters for the entire site. Soil water-holding capacity, water table, and nitrogen availability are plot-specific parameters based on soil type. Plots in a riparian corridor, for example, may have a shallower water table

than do plots in nearby shelterbelts. Currently, the model is designed to represent landscapes up to 1 km<sup>2</sup> in size.

Seed dispersal is an especially important component of these fragmented landscapes, as it plays an important role in the availability of seeds to colonize a plot (Hanson et al. 1990). Most models based on JABOWA or FORET assume contiguous forests with ubiquitous seed dispersal, where seeds of all species are assumed to have an equal probability of dispersing to the modeled plot. For patchily distributed forests such as those found in the Great Plains, this assumption is unrealistic. Using SEEDFLO, Hanson et al. (1990) modeled the dynamics of an array of linear riparian forests in the Great Plains. Their model included functions for species-specific seed dispersal among patches, and the effects of landscape fragmentation on dispersal. Their results showed diversity to be inversely related to fragmentation, and a greater abundance of species with high probabilities of dispersal, such as bird-dispersed species. Models such as these that specifically incorporate dispersal functions represent a significant development in the application of forest dynamics models to Great Plains forests, which are characteristically scattered in their distribution.

SEEDSCAPE is designed to combine consideration of seed dispersal and varying water table with an accurate representation of a patchy forest landscape. This better enables us to predict potential effects of potential climate change on the small portion of lightly managed land

in an otherwise intensely managed agricultural landscape. These effects, while occurring on a small portion of the total land area, nevertheless have important implications for biological diversity of both plants and animals, as well as for agricultural production.

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# 245 Collaborative Decision Process Support Tools from Global Change Research<sup>1</sup>

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## Introduction

The global change research program is a major research activity designed to improve understanding of ecosystems and, in particular, how they respond to global change stress. The term "Global change" includes global climate changes caused by human activities, population growth, increasing air, water and land pollution. Global change can be thought of as a package of the large scale issues in our current world environment that impact natural ecosystems. Global change acknowledges that humans are significant components of the world's ecosystems. It further implies the philosophy that humans ought to "do something" about the situation. The "something" is being defined globally at present, but a number of manifestations of the movement are already apparent and quite real. To name a

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few, the Global Climate treaty is considering country by country limitations on greenhouse gas emissions, the Biodiversity treaty is mandating maintenance and enhancements of biodiversity and the desertification treaty is just beginning a world wide dialog on how to stem growing desertification. Although these are global movements, the nature of environmental activism and public concerns requires that they be addressed locally. The popular bumper sticker, "Think globally, act locally" illustrates the concept.

The global change research program within the Forest Service has developed to provide scientific support for this mission, namely, to define the sort of "local action" appropriate in the face of global change stresses. In particular, what sorts of management actions should we advocate to maintain sustainably healthy and productive ecosystems? Among the components of this very complex task, are scientific efforts to understand ecosystem behavior and to package that understanding in models having the capability to predict system response to management actions taken under global change scenarios. The results of this re-

**Abstract.**--Global change research attempts to develop a predictive understanding of ecosystems, especially their response to a host of anthropogenic stressors. In particular, the Forest Service component of this program is concerned with how forest and related ecosystems should be managed in view of this understanding. Collaboration among scientists, managers and resource stakeholders is a key requirement for achieving improved management. This paper discusses a set of tools currently under development, that are capable of assisting people in conducting collaborative decision processes. It reviews recent advances in collaborative GIS techniques, describes an application of collaborative GIS with the Arapaho-Roosevelt National Forest, and discusses future development efforts.

search will be useful to managers. It will provide them tools to help predict alternative ecosystem futures and the role of their management decisions. These models will be useful for advancing management through the use of better science and more direct involvement of scientists and resource stakeholders in decisions.

Currently land managers are moving toward greater dependence on models to assist in sorting out the consequences of management actions. More people will become involved and the decision processes the agencies will pursue will become more collaborative. For example, the essence of adaptive management is using the **feedback** of data from monitoring the consequences of an action to **adjust** future actions. There needs to be a collaboration between a number of people in this activity, not the least between interested publics and scientists and managers.

Collaborative decision processes are gaining increased interest within the Forest Service as well as other natural resource agencies. This is driven, in part, from acceptance of the concepts of adaptive management being advanced

through the experiences of managing valued natural resources within an adversarial environment. Adaptive management, for example, has been one of the major "solutions" proposed by the President's Plan for forest ecosystem management in the Pacific Northwest. In that plan adaptive management is further explained as a people driven process, stating that:

"People will not support what they do not understand; and cannot understand that in which they are not involved" (Callopy et al. 1993).

Similarly, a human dimensions study group assembled by the Forest Service Southwest Region and the Rocky Mountain Station suggests strategies for implementing human dimension principles, that require involving stakeholders in determining the trade-offs between current use and future options; Developing desired future conditions that meet the collective needs of people and physical-biological systems; utilizing collaboration processes for planning ecosystem management, utilizing collaborative analysis and design processes involving all stakeholders, among others. They conclude that:

"Strong collaborative partnerships with stakeholders are required." (Human dimensions study group, 1994)

In this paper, we present tools and technologies capable of assisting collaborative decision processes. These tools and technologies depend on the availability of integrated spatial information, such

as is the vision on which the Forest Service "615" program is based. After a brief discussion of adaptive ecosystem management, we introduce collaborative GIS, a new science spawned by linking groupware and GIS. Next, we review a recent application of the Active Response GIS (AR/GIS) to the Arapaho-Roosevelt National Forest Plan revision process. And, finally, we present thoughts about future capabilities.

### **Adaptive Management: Using Science to Improve Management**

Adaptive management has developed from the original ideas of Hollings (1978) and Walters (1986). As Bormann et al (1994) point out, the concept is similar to "Total Quality Management" in business, "hypothesis testing" in experimental science, and feedback in control theory. The essence of adaptive management is using data about an action to adjust subsequent actions. While there are many ways to implement adaptive management, activities have been grouped as adjustment decision processes, linked actions (across scales and ownership), feedback, and information synthesis (Bormann et. al. 1994). These activities share the common requirement that groups of people must interact with data and information, apply analysis tools and arrive at some consensus for them to be effective.

Adaptive ecosystem management will be demanding for managers to practice. It will require more and better data, more refined analysis, improved people skills and more powerful technologies than we have used in the past.

Fortunately, the "615" project offers the promise of providing much of what is needed. There remains, however, considerable work to be done in developing data and information frameworks capable of crossing scales, administrative boundaries and disciplinary barriers. Much of the science being developed under the global change research program will prove useful for the post "615" adaptive management era.

### **Data, Analysis, and Collaboration**

Geographic data are the backbone of modern ecosystem management. The term implies that all of the data utilized in any analysis of the past, current and potential future conditions of a region are geographically specific. Information is not general but is place specific. Achieving uniform spatially based data coverage, particularly over large regional areas is difficult and is the subject for considerable discussion in its own right. For adaptive ecosystem management, such geographic data must include coverage for all the issues being addressed, without inconsistencies between boundaries of land ownership and management responsibility. Sufficient coverage includes geographic contexts for resource capabilities, resource utilization, and resource potential. Also, geographic data about specific management activities past, present and potential future are needed. Creating this coverage is such a big job that we will not be able to afford to do it more than once and without broad collaboration between all stakeholders.

**Scientific analysis** means, in the context of this discussion, geographically specific science that improves our understanding of the ecosystem and our ability to predict its potential responses to perturbations both natural and anthropogenic. This scientific analysis will no doubt require a wide array of technologies and tools in order to provide such predictions. To the extent that the ecosystem itself may be non-deterministic and chaotic, these scientific analyses will likely be stochastic providing probability based estimates of potential futures. However, the primary point we wish to reinforce here is that this science, to be most useful for adaptive ecosystem management, must also be place based, geographically specific and applicable to the issues and at the scales that are being addressed. This will require a methodology to link existing models from a wide variety of sources and scientific perspectives. The Modular Modeling System under development by a team of researchers including TERRA is a tool that supports such a methodology.

**People** are the prime focus of this presentation. Land management has always been about people and their values, however, this has been reinforced by FEMAT, Plan appeals, and a host of other recent Forest Service experiences. It seems likely that more people will be involved in Forest Service ecosystem management than have been involved in earlier land management. Not only more people, but people representing a widening diversity of opinion, using increasingly sophisticated tools and demanding consideration of their view points. The Federal Advisory Committee Act (FACA) presents a

further challenge to this trend requiring considerable attention and careful design of public interactions. In addition, more people within our Agency are involved with the decision-making process. They are members of multi-disciplinary ID teams, specialists from other federal, state, county, Tribal and local governments (assuming FACA is amended accordingly). The point is that with elected officials, land owners, and permittees added to the picture, there are lots of stakeholders. We need efficient means to capture their values and their contributions, and to allow them to participate in an efficient and meaningful manner. People need to be provided opportunities to be a meaningful part of the process. This paper will discuss a set of tools that are designed to help accomplish these goals.

"Collaborative Decision Process Support" is a term we use to describe a set of tools and technologies we have been developing at TERRA over the past 3 years. Collaborative decision processes are group processes in which all participants have equal access to relevant data and information. That information is both available and understandable to the stakeholders. By law, final consensus and decisions might need to be restricted to appropriate authorities, but, especially in this case, those decisions are subject to considerable scrutiny and review. Computer based tools and technologies can facilitate the collaborative decision process. A number of decision support systems for ecosystem management are under development. All of these systems involve the utilization of geographic data and analysis. For them to be most applicable to adaptive ecosystem manage-

ment, we suggest they will need to add the ability to interface with groups of people. Collaborative GIS can provide such value adding for the next generation of decision support systems.

## Modular Modeling System

Adaptive ecosystem management requires spatially oriented models of physical, chemical and biological processes capable of application at many different spatial and temporal scales. Further, it requires the integration of models from many disciplines as well as the desirability of making the numerous models available to all stakeholders to the decision process. Among the greatest public participation disincentives are complex models that are neither accessible nor understandable. Adaptive ecosystem management applications require changes in the models that will insure compatibility and linkage. These changes need to be accomplished in a way that minimizes the effort involved.

Toward this end, TERRA has participated in a team effort with George Leavesley (USGS-WRD) and Pedro Restrepo formerly with the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) to develop a modular modeling system (MMS). MMS automatically links selected modules, runs the assembled collection of modules, and presents the results in graphical and three dimensional displays. This system has progressed to the point where a users manual to MMS was completed and the system is available to anyone from the TERRA Home Page on the Internet (URL <http://>

www.terra.colostate.edu). The manual describes how the software is structured and how to use it to develop models using modules that reside in the system. It describes how to modify existing models to place them into the system. The manual also describes how the system links the modules and how to set up, run and structure the output of the linked system (CADWES, 1994). A link to GIS (GRASS at this point) was completed and is in the latest version. An approach to allowing a feedback loop between models and model components is also incorporated in the latest version of MMS and is currently being tested. A Object Oriented version of MMS is currently underdevelopment. MMS is available as a tool for scientists and other modelers who are interested in linking their models broadly across a wide array of potential users.

### Collaborative GIS

A collaborative GIS is a geographic information system which has been extended from a single-user tool to incorporate group interaction with geographic data sets. While a single-user GIS is typically used by a trained professional for manipulating large geographic datasets, collaborative GIS is a new technology aimed at helping possibly non-technical decision makers when discussing, exploring, and negotiating resource alternatives.

Faber et al (1994a & b) discuss the need for a collaborative GIS by pointing out "information bottlenecks" inherent in a resource management process supported by single-user GIS technology.

- A GIS professional is required to extract data and perform analyses, forcing resource managers to anticipate and schedule data requirements well in advance.
- Because negotiation sessions typically make use of hardcopy output for reference, complete data and/or recent changes to the data may not be available.
- Use of hardcopy or a single-workstation display limits meeting participants' ability to study or highlight areas of individual concern.
- Use of hardcopy or single-workstation display does not allow negotiators to discuss or build upon solutions developed by other group members.
- Because analysis of recommended changes (digitization and data integration) can take weeks or months, it is not possible to assess the implications of a suggested approach within the context of its initial recommendation.
- Decision rationale, arrived at verbally, is irretrievable for subsequent public inquiry and regulatory review.

Collaborative GIS technology seeks to address these information bottlenecks and to improve efficiency of resource negotiations.

### The AR/GIS System

The Active Response GIS (AR/GIS) is a collaborative land resource negotiation system developed at the TERRA Laboratory in Fort Collins, CO. It is an integrated system which incorporates GIS capability into an electronic meeting system (EMS) architecture. A wide array of commercially-available EMS products offer the capability to capture meeting participants' votes, comments, or positions via an electronic input device, and then summarize all input for the group (fig. 1). Key characteristics of an EMS environment include:

- simultaneous input, allowing everyone to state their position or opinion at once;
- anonymous input (if desired), which can minimize the effects of dominant personalities and preestablished group hierarchies;
- summarized display of all input for group review; and,
- automatically generated meeting documentation, available for review at any time.

Electronic meeting system architecture encompasses input devices which are connected via a local area network. The system software has a client/server architecture with a file server collecting all data generated by participants. A special facilitator controls the software. A video display device is connected to the facilitator's computer to display results to the group. Printers, external databases,

and other devices may also be included on the network.

The AR/GIS collaborative GIS adds a geographic framework to the EMS environment. It provides an interactive, real-time environment for teams of resource managers to debate land allocation issues. Participants are electronically "linked" through a PC-LAN configuration of laptops. Participants construct potential geographic scenarios. The implications of these scenarios are modeled and discussed with the group as the scenarios are suggested. Decision rationale for final recommendations are recorded automatically and linked to the original geographic datasets.

## Collaborative GIS Capabilities

The AR/GIS system includes the following collaborative geographic interaction tools.

### Geographic Exploration Tool

This tool allows negotiators to interactively explore supporting data via a simple menu interface. Data may include geographic data layers, economic statistics, policy statements, photographs, etc. Participants customize presentation of the geographic data to fit their own perspective (e.g., overlay selected landmarks, zoom into particular regions, highlight areas of interest). Thus, the

negotiators are no longer dependent on GIS technicians for data review and access.

### Geographic Proposal Tool

This tool allows graphical submission, compilation, and tracking of geographic proposals via annotated data layers. Each participant constructs geographic proposals by using a computer mouse to "trace" regions on various data layers. From a technical standpoint, each set of traced regions constitutes a data layer of digitized polygons which graphically captures the participant's perspective or position. The outcome of this activity is a new GIS data layer generated by each participant. Thus, a full array of analysis techniques may be applied to combine and analyze this data for display to the group. The implications of various scenarios can be modeled and discussed during the meeting as they are generated.

### Geographic Prioritization Tool

This tool uses electronic voting/prioritization utilities to establish land management priorities as weighting factors for subsequent geographic analysis and modeling. Participants first use a groupware voting application. For instance, they might rank the importance of land characteristics or score objectives based on a multi-criteria land-use objective. The resulting combined scores from this exercise are then applied as weighting factors for any number of GIS analysis techniques.

## Electronic Meeting System Architecture

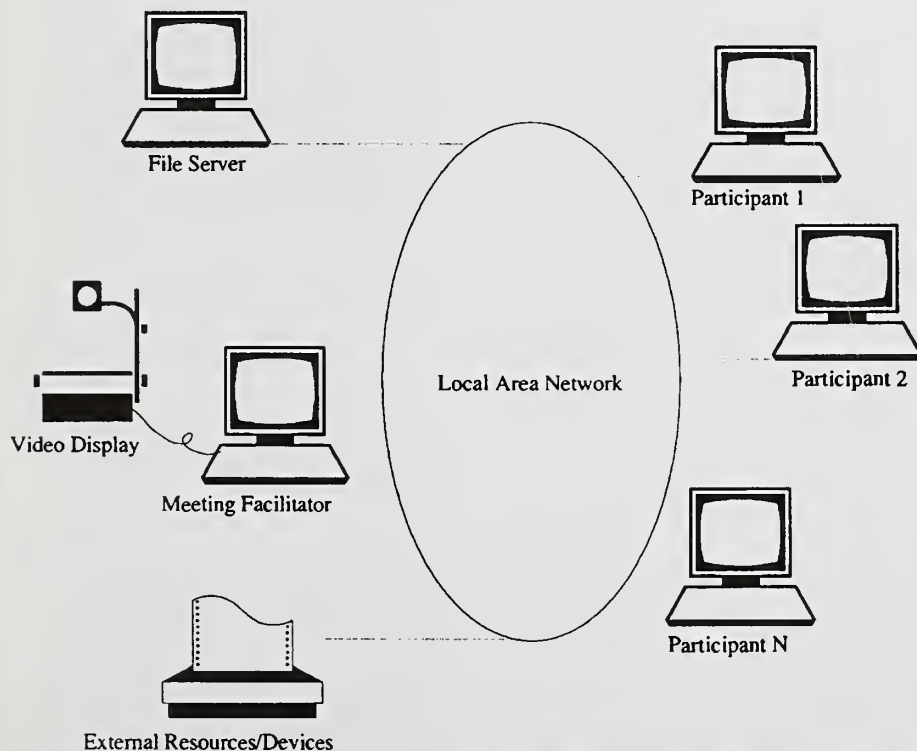


Figure 1.—Electronic meeting system architecture encompasses input devices which are connected via a local area network. The system software has a client/server architecture with a file server collecting all data generated by participants. A special facilitator controls the software. A video display device is connected to the facilitator's computer to display results to the group. Printers, external databases, and other devices may also be included on the network.

## **Database Link to Spatial Changes**

This tool provides the capability to track decision rationale for changes made to data layers during a negotiation session. If a database of initial issues is available, map changes can be linked to the appropriate database record(s) to document how each issue was addressed. A map change can be retrieved by clicking on an issue in the database, or conversely, the prompting issue can be retrieved by clicking on an area of the map. In addition, map changes negotiated by the group are tagged with a rationale statement with captures the essence of the discussions leading to the decision. This ensures that a record of decision rationale is maintained and is readily accessible for public inquiry and regulatory review.

## **Geographic Negotiation Tool**

This tool involves the use of a whiteboard to encourage participant interaction and collaboration. Data layers displayed on a facilitator's workstation are projected on a whiteboard using a video display device. Then, in a method similar to the Geographic Proposal Tool described above, participants work together to propose land-use scenarios by interactively tracing/erasing areas with marker pens. This encourages the group to collaborate verbally to generate a group proposal. Once the group agrees on a proposal, the meeting facilitator captures this work by tracing the pen marks overlaying the projected display with a mouse. A full array of analysis techniques can now be applied to combine and analyze this data for further discussion.

## **Application of Collaborative GIS on the Arapaho-Roosevelt National Forest**

The collaborative GIS techniques described above were recently used by the Arapaho-Roosevelt National Forest for their Land Management Plan revision. The Arapaho-Roosevelt management team shares a vision of simplifying the process using a "real-time planning approach." The new approach would incorporate an adaptive management process where, through continuous monitoring and evaluation, district staffs would dynamically adjust the plan to address changing issues and conditions as they occur. A collaborative GIS environment, allowing hands-on interaction with the Forest Management Plan for both district personnel and their public, was seen as an exciting first step to this real-time planning vision. Thus, a pilot study was designed to assess the viability of collaborative GIS for resource planning and negotiation. The ongoing Arapaho-Roosevelt Revision process provided an ideal environment for testing this approach.

This project was initiated late in the Revision process. A preliminary draft of management area allocations had already been introduced. Public response to the initial draft had been collected through a variety of mechanisms including open houses, field trips, and individually submitted forest plans. It was time for the district rangers and their staffs to respond to public comment by making final alterations to the Forest proposal.

The AR/GIS collaborative GIS system was introduced to the

planning process in 2- to 3-day workshops held with district personnel at each of the six districts within the Arapaho-Roosevelt National Forest. The portability of AR/GIS (laptop computers and a local area network), made it possible to conduct the workshops at each district office. The purpose of the workshops was to address public comment and to finalize district-specific management strategies. The districts used the AR/GIS collaborative GIS system to explore district priorities, review the database of public comment, and respond by suggesting changes to management prescriptions, prescription boundaries and/or general policy.

The workshops produced a carefully considered response to each comment received from the public, updated drafts of the Revision Plan incorporating district-level detail and attention, and a rationale for each change, to be maintained in the administrative record.

## **Participant Evaluation of the Process**

At the close of each workshop, participants were asked to comment anonymously on the value of the collaborative GIS system to their revision process. It is worth noting that the majority of the district staff participants had limited or no exposure to personal computers prior to the workshops. Following is a paraphrased sample of some of the comments received.

In what ways did the collaborative GIS system improve your process?

1. It provided an efficient way to review, make changes, and consider public comment.
2. The biggest contribution was the ability to make changes and record decision rationale right in the meeting, without having maintain separate documentation.
3. The system allowed us to compare alternatives very easily.
4. The large projection on the whiteboard was helpful for changing boundaries.
5. The anonymity of the voting tool helped to ease us through some difficult issues.
6. I think everyone gained ownership in the decisions and had a chance to express their concerns. I have a better understanding of GIS technology and its capabilities.

In what ways did the collaborative GIS system hinder your process?

1. Learning the system took extra time, but once learned it was easy to use.
2. Often only a few people were making changes while all others were waiting.
3. We needed more landmark overlays on the system like towns, peak names, and elevation lines.

4. The extra time required to familiarize ourselves with hardware and software could have been used for concentrating more thoroughly on the issues.

## **Future Enhancements and Research**

### **Modular Modeling System**

Future work on MMS is focused on adding an object oriented flow routing, arroyo dynamics and sediment transport process simulation for application in the TERRA Rio Puerco Watershed Project.

### **Continuation of the Arapaho-Roosevelt Project**

Following release of the Management Plan Draft, the allocation changes and rationale used to develop the Plan will be made available for public review and inquiry. The AR/GIS system's role in this process will be to allow the public, within a workshop environment, to explore alternatives and environmental effects information at their own pace, suggest additional allocation changes, and leave comment for Forest officials. This has advantages over typical public presentation formats because it allows individuals to review the information they are most interested in and provides a dynamic means to make suggestions and/or work out compromises. Completion of the Management Plan Revision Process is scheduled for year-end 1995.

In the long-term, the Arapaho-Roosevelt team plans to continue developing a real-time planning system. Primary focus of this work

will be on developing real-time impact assessment techniques, and on increasing staff/public understanding of interactions between management strategies and environmental conditions. The team plans to continue development of the collaborative GIS tool, with special emphasis on integrating ecosystem assessment models into the system.

### **Distributed Internet Version of AR/GIS**

While the AR/GIS collaborative GIS is designed specifically for face-to-face negotiations, a demand is growing for a similar mechanism to support remote land-resource negotiations. For example, a land management plan may require public input from local land managers, coordination support from regional agency representatives, and policy input from governing bodies at the state or national level. TERRA is working on a prototype distributed land-resource negotiation tool. This tool will encompass many of the capabilities of the AR/GIS prototype, and will be customized to operate in a distributed mode using an Internet framework. Cooperatively with IBM, we are planning to implement a distributed version of AR/GIS on the Forest Service "615" desktop.

### **Research on Implications to Social Justice Theory**

TERRA, in collaboration with the Colorado State University Psychology Department, is investigating the impact of using collaborative GIS on perceptions of social justice in planning and policy negotiations. Studies are under way to determine if a collaborative GIS, which allows

negotiators to review and comment on geographic issues independently, will increase perception of "voice" (i.e. active individual contribution) in the resource negotiation process. Existing research in social justice indicates that increased perceptions of voice are correlated with increased perceptions of fairness and acceptance of both favorable and unfavorable process outcomes.

### Linkage with Other Analytic Tools and Decision Support Systems

The next version of AR/GIS will be implemented using ArcView 2 as its GIS interface. ArcView 2, as a result of "615", will be widely available throughout the Forest Service, and provides an environment for interfacing PC based applications with UNIX based applications. DSS systems developed for either platform will be able to access and incorporate AR/GIS. In addition, TERRA has been working cooperatively with the U. S. Geological Survey and others for the past three years to develop the Modular Modeling System. MMS is a UNIX based model assembly and organization tool. It is designed to facilitate the addition of model components, testing of alternative formulations of models and simplify visualization of model outputs. Many of the decision support systems identified above should find MMS to be a value adder in the sense that it can facilitate linkage between different systems. For example, a DSS might wish to conduct an analysis using a sophisticated hydrologic model. The DSS might call upon MMS to manage the model assembly, data requirements and runs.

### Summary

Adaptive ecosystem management is a continuous process that requires involvement and interaction of groups of people at all stages in its activity. These groups need to be able to interact with geographic data, with analysis tools and with the results of the analysis presented in readily understandable formats. Decisions that are made within this context will require sophisticated support systems to ensure their quality and their consistency. The AR/GIS collaborative GIS combines GIS and electronic meeting software to assist land managers in the conduct of adaptive ecosystem management. The AR/GIS system has been successfully applied in a National Forest Management Plan Revision effort. Future work includes increased analysis capability, extension to the Internet environment, and studies relating to social justice implications.

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